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RECENT PROGRESS IN POLYMER DRAG REDUCTION

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Recent developments on various aspects of polymer friction reduction in turbulent flow are reviewed, with special emphasis on the areas where intensive work is currently under way. Detailed attention is paid to the topics of drag-reducing suspensions, heat transfer in polymer solutions, and the effect of polymers on cavitation, jets, and lift.

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NAVAL UNDERSEA CENTER, SAN DIEGO, CA. 92132

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

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ADMINISTRATIVE INFORMATION

SUMMARY

PROBLEM

Prepare a review of the literature on drag reduction through the use of high-polymer additives.

RESULTS

Recent developments on various aspects of polymer friction reduction in turbulent flow are reviewed, with special emphasis on the areas where intensive work is currently under way. Detailed attention is paid to the topics of drag-reducing suspensions, heat transfer in polymer solutions, and the effect of polymers on cavitation, jets, and lift.

RECOMMENDATIONS

The Navy should continue a strong interest in the hydrodynamics of polymer solutions in order to exploit the unusual properties of these fluids.

CONTENTS

INTRODUCTION

Polymer drag reduction, an effect which shows itself in reduced flow friction when trace quantities of high-polymer substances are present in the flow, is easily demonstrated both in the laboratory and in the field. Many papers confirming and extending the details of the friction-reducing effect have appeared since the last major review [1] in 1972.

These papers have filled in many gaps in our knowledge of polymer flow properties, but much more remains to be learned. In particular, progress in the theoretical understanding of the mechanism of drag reduction has been very slow.

As a historical note in the story of turbulent-flow drag reduction by polymer additives, the experience of Mysels and his students during World War II in pumping gasoline and gasoline with dissolved aluminum soaps has now been recounted [2] and firmly establishes Mysels as a pioneer in the drag-reduction field.

RECENT DEVELOPMENTS

PIPE FLOW

In the last few years, pipe-flow work with polymer additives seems to have concentrated in four main areas: the study of new polymer-solvent pairs, which either add new insight to our knowledge or may be used in solving practical problems; the development of new flow-visualization techniques, which aid in understanding the change in flow processes when polymers are present; the study of pulsed flow of polymer solutions; and an intensive review of the breakdown or degradation of polymer molecules due to the stresses of turbulent flow in pipes.

Before these topics are discussed, however, several important new results in the pipe flow of well-known polymers should be emphasized. The work of Tullis and his students [3] has extended our knowledge of drag reduction effectiveness to Reynolds numbers of 3×10^6 in a 12-in. diameter, 200-ft-long steel pipe. Using poly(ethylene oxide), Tullis showed (figure 1) how the drag reduction varies from the point of initial injection of the polymer near the wall of the pipe to the more thoroughly mixed region at the end of the pipe. Initially, drag reductions of 80 % or more are achieved.

Kelkar and Mashelkar [4] showed that drag reduction occurs in helically coiled tubes as well as in straight pipes, and Rubin and Elata [5] found that drag reduction is possible in an annular pipe. It has also been found [6] that two-phase (gas-liquid) flows reduce friction when high polymers are added to the liquid phase; thus almost every pipe-flow geometry has been shown to produce drag reduction with polymer.

New Polymer-Solvent Pairs

Parker and Hedley [7] studied a polyacrylic acid of 20×10^6 molecular weight and found remarkable drag reduction performance at a pH of 6 to 8. As shown in figure 2, a lowering of the pH to 2.2 greatly reduced the drag reduction, showing the important effect of pH in controlling the molecular extension and thus the drag reduction. At the most extended condition (pH = 8.2) the polyacrylic acid was a more effective drag-reducing agent than poly(ethylene oxide), both on a weight and molarity basis. In addition to pH, the temperature is a parameter in the effectiveness of some drag-reducing polymers, for example, polyacrylamide. Pike [8] found that while the pipe flow of poly(ethylene oxide) solutions was unaffected by reduction of the fluid temperature to 3 °C from an ambient of about 14 °C, two types of polyacrylamide gave only about half the drag reduction observed at the higher temperature. Other polyacrylamides have shown less temperature sensitivity [9]. Modifications to the polyacrylamide molecule to achieve better drag reduction performance also were described [10,11].

Extensive experimental investigations of algal, bacterial and plant polysaccharides as friction-reducing agents were reported [12]; a linseed-gum extract gave approximately the same friction-reducing performance as the well-known guar gum, and an algal polysaccharide

gave more friction reduction, after being subjected to strong shear, than polyacrylamide. Other rather exotic friction-reducing materials can be found listed in a catalog of drag-reduction effectiveness [13].

Zakin and Chiang [14] found that a non-ionic surfactant complexed with sodium salts was a good drag-reduction material, even at very high shear stresses, while aluminum disoaps in toluene show excellent performance in reducing friction, especially in the presence of small amounts of water, but are unstable and lose their effectiveness after a few days' storage [15].

Perhaps the most interesting work has been with solutions of polystyrene in toluene and other solvents. A rather high molecular weight is necessary for friction reduction with polystyrene (because of the bulky side chains) and molecular weights 2×10^6 or more are needed to demonstrate the effect [16]. Since the polystyrene molecule has been rather well studied, and because it can be prepared and characterized easily, work using this polymer may lead to important insights as to the mode of action of drag-reducing macromolecules.

Finally, the ultimate use of water-soluble polymers in industrial, commercial, or government activity may depend on the acceptance from a pollution standpoint of these materials in rivers, lakes and oceans. It is reassuring to note from Wade [17] that poly(ethylene oxide) and polyacrylamide were found to be completely innocuous to marine algae, bacteria, and animals at concentrations far greater than ever expected to be found in the environment.

Flow Visualization and Measurement

The possibility of polymer solution measurement errors with pitot tubes were reemphasized [18] as were the problems with piezoelectric probes [19], and hence workers turned to flow visualization and measurement techniques that avoid a probe in the flow in order to obtain quantitative measurements. Dyes, electrochemical phenomena, gas bubbles, tracer particles, and the laser-doppler anemometer were explored as possible means of showing changes in flow structure when polymers are introduced into the flow.

One of the most interesting studies was that of Donohue, et al. [20]. When dye is introduced into the viscous sublayer of a turbulent flow, the initially smooth and uniform layer of dye is soon formed into longitudinal streaks corresponding to lower-velocity areas in the flow near the wall. The non-dimensionalized spacing of these streaks is roughly constant for low-speed water flow, but when polymers are present in the flow, the streak spacing is greatly increased, as shown in figure 3. In addition, and more importantly, the low-speed streaks periodically lift away from the wall into the buffer region, where they oscillate and then burst violently away from the wall region. These bursts can also be visualized by the dye technique, and as shown in figure 4, the number of bursts is reduced by as much as 70 % when polymers are present in the flow. Thus a tentative explanation of the mechanism of drag reduction is implied by this visual experiment, but of course the reason for this behavior is still largely unknown. Even larger increases in the streak spacing

were reported by Fortuna and Hanratty [21] and Eckelman, et al. [22], in this case using an electrochemical technique.

Observations of bubbles in the flow can be used to derive velocity profiles, either by study of pulsed bubbles using a hydrogen-generating wire in the flow, or by a stroboscopic lighting technique. White [23], using the hydrogen bubble technique, obtained velocity profiles for a complex soap under conditions of maximum drag reduction. These profiles resemble laminar-flow profiles more than the blunt profile typical of turbulent flow. Rollin and Seyer [24], using stroboscopic light to illuminate air bubbles and form traces on film, indicate that the velocity profiles for a dilute (0.01 %) solution of polyacrylamide are flatter than a water profile, but as the concentration is increased to 0.10 % the profile becomes more laminar-like. Gebel and Reitzer [25] used a small-particle tracer and a photographic technique to study the flow around a circular cylinder with and without guar gum in the flow.

Using another visualization technique, that of a dye compound dissolved in the flowing fluid, which changes color when illuminated with a flash of light, Arunachalam, et al. [26], produced streak photographs, which show that weakly drag-reducing solutions produce a thickened boundary layer and a blunt profile; a strongly drag-reducing solution shows a very laminar-like profile.

This general trend seems to be confirmed by measurements using laser-doppler velocimeters. In this technique, small particles moving with the local flow are illuminated by laser light, and the doppler shift of the scattered or reflected light from the moving particles is measured by sophisticated instrumentation. Data from Rudd [27, 28] and Chung and Graebel [29] all seem to agree that in general, good drag-reducing polymer solutions have a velocity profile more blunt than does the pure solvent, but tend to become more laminar-like as the polymer concentration is increased above optimum levels. A Reynolds number effect is also present, making the generalization rather a rough one.

The most recent laser-doppler data on polymer solutions are those of Reischman [30]. His data indicate the velocity profile is affected not only by the amount of drag reduction and the Reynolds number but also the type of polymer used; polyacrylamide profiles seem to have a different shape than those of poly(ethylene oxide), for example. Reischman's near-wall turbulent intensity data are of interest also, since he found a much smaller increase in turbulent intensity near the wall when polymers are present than did both Rudd [28] and Logan [31]. The plot of his data (figure 5) shows a large difference in intensity compared with that of Rudd; a partial explanation could be that Rudd (also Logan) used square pipes possibly subject to secondary flows, while Reischman used a high aspect-ratio rectangular duct. However, Kumor and Sylvester [32], using a flat plate, appear to confirm Rudd's values. Clearly the elucidation of the details of the near-wall changes in the flow when polymers are present is an area of research requiring much more effort.

Pulsed Flow

The interest in pulsatile flow of drag-reducing polymers stems from the possibility of their use in the body as therapy to lower the flow resistance in cases of restricted or blocked

6

arterial vessels, and from the recent discovery that friction reduction can be achieved in pulsed laminar flows of polymer solutions.

As shown in figure 6, Voitkounsky, et al. [33], demonstrated that pulsating laminar flows of polymer solutions can reduce friction. The greatest amount of friction reduction corresponds to optimal relaxation properties of the polymer. This notable result indicates that polymers can be effective in any flow in which there is a finite rate of change of strain with time. Recent theoretical work [34,35] provides a firm basis for the observed drag reduction in pulsed laminar flow.

The idea of using drag-reducing additives in the blood stream to aid cases of heart disease or atherosclerosis by reducing the pumping power required seems attractive [36]. Among the most promising polymers is the natural polysaccharide okra [37], which has the advantage of good compatibility with blood, having been used as a blood plasma substitute. In pulsile flow, okra gives a good friction-reduction effect, extending to Reynolds numbers below the normal transition for Newtonian fluids [38]. The pressure drop across artificial heart valves was also greatly reduced by okra solutions [39].

Pulsed flow studies of polymers in blood [40] and other fluids [41] indicate that sizable drag reductions are obtainable, and it is clear that work in this area may lead to important medical applications of drag-reducing polymers.

Turbulent Diffusion

A surprising amount of recent work has been devoted to the topic of diffusion of polymer molecules through the boundary layer, as would be the case when polymers are injected into the flow for diag reduction. Also there has been much work on polymer diffusion through bulk liquids.

The turbulent diffusion is greatly reduced by polymer additives, in pipe flow [42], on a flat plate [43,44], and in bulk liquid [45]. However the dispersion (i.e., the rate at which tracer is convected downstream) is increased in pipe-flow [46] as well as in an open channel [47] when polymers are present.

Polymer Degradation

Kenis [48] was able to show, by repeated passes through a small pipe-flow apparatus, that some highly effective drag-reducing polymers appear to break up or degrade with mechanical shear and thus lose their effectiveness. Other polymers having initially poorer performance, but less subject to degradation, could be more effective in long-term shear applications. Figure 7 shows the type of data Kenis obtained. Subsequent investigations [49–54] have characterized various drag-reducing polymers in essentially the same way. Wade and Kumar [55] collected samples after each pass of polyacryamide through a small pipe-flow apparatus and examined the apparent molecular size distribution using an electron microscope. Analysis indicated that the average molecular weight fell from about 7×10^6

before the test to about 10^6 after 10 passes through the pipe, the larger molecules being most subject to shear. In another degradation study, Kumor and Sylvester [32] show how the near-wall velocity profiles change with degradation.

ROTATING DISKS

A disk rotating in drag-reducing fluid is a convenient experimental technique to demonstrate the reduction of friction, and to evaluate various polymer parameters. It is the simplest experimental arrangement of an external flow. Recent progress has been made in this field in the areas of evaluating new polymers, strengthening the theory of disk flows in friction-reducing solutions, adopting electrochemical techniques, and the use of a rotating disk as a degradation evaluation instrument.

Experimental Studies

Kato, et al., [56] made a thorough study of an enclosed disk rotating in various molecular weights and concentrations of poly(ethylene oxide). They also evaluated the streamlines around the enclosed disk under different conditions by cementing threads to the disk and using stroboscopic photography. The streamlines around an open disk were studied by Bilger [57], who made streak lines by painting the disk with a thin layer of carbon black and oil. Bilgen showed how the streak spacing and flow angles are greatly increased in polymer solutions as compared with pure water.

Bilgen has also studied polymer flow around an enclosed disk [58], a disk simulating a seal adjacent to a fixed surface [59], and the flow between concentric cylinders [60]. Other recent experimental papers dealing with rotating disks are those of Peyser and Little [61], who studied the effect of different types of solvent on drag reduction achieved with polystyrene (a good solvent gives more drag reduction than does a poorer one), and the work of Kale, et al., [62] who found that rather concentrated polyacrylamide solutions (0.5-2%) give a lower drag in laminar disk flow than does a Newtonian liquid.

Theory

Important contributions to the theory of a disk rotating in dilute polymer solutions were made by Tomita and Mochimaru [63], Bilgen and Vasseur [58], and especially by Granville [64]. Figure 8 shows how Granville's theoretical prediction of the maximum drag reduction in polymer solutions compares with available test data. Bilgen's analysis yields a simpler formula:

$$k_m = 0.360 \, Re^{-0.359}$$

which also approximates the data fairly well.

Correlations of drag reduction data for rotating disks were made by Peyser and Little [61] and Mashelkar [65]. These correlations are based upon the demonstration that the

8

friction factor should be a function of both the Reynolds number and the Deborah number (ratio of some characteristic relaxation time of the fluid to some characteristic flow or process time). It would be interesting to attempt such a correlation, using the full range of rotating disk data available in the literature [1]. A similar type of correlation for pipe flow is given by Wang [66].

Electrochemical Techniques

Hanratty and his students [67] pioneered in the use of electrochemical techniques in the study of drag-reduction in pipe flow. Another pipe-flow study is that of Sidahmed and Griskey [68]. The use of rotating disks in laminar non-Newtonian fluids also were studied [69], but only recently was a technique worked out [70] that may be applicable to the turbulent flow of dilute drag-reducing fluids.

Recently Deslouis, et al., [71] showed how drag reduction leads to a reduction of the limiting diffusion current in an electrochemical reaction. By using an annular ring electrode buried in the surface of an insulated disk, the local friction in a narrow annulus of the disk can be measured, rather than the integrated drag as is usual in hydrodynamic techniques. Initial tests [71] show that drag reductions of 50 % or over can be inferred from the diffusion flux measurements in turbulent disk flow with 4-ppm poly(ethylene oxide) in the electrolyte fluid. This new technique offers considerable promise in the study of the details of the flow over a rotating disk in polymer solutions.

Degradation Studies

Gold [72] used a rotating disk apparatus to show the degradation, with prolonged shear, of dilute polymer solutions. An interesting aspect of the work was the finding that relatively concentrated solutions (1 %) of poly(ethylene oxide) could be sheared so as to reduce their viscosity by over 50 %, but this viscosity reduction had no effect on the subsequent drag reduction when the concentrated solutions were diluted to a few parts per million. Figure 9 shows a typical result. The work is of interest in that there seems to be a different mode of action in viscosity-reduction in concentrated polymer solutions as compared with friction-reduction lowering in dilute solutions, when both are subjected to intense shear forces. The polyacrylamides have been shown to be much more stable to prolonged shear than poly(ethylene oxide). Abdel-Alim and Hamielec [73] studied polyacrylamide degradation in a concentric cylinder viscometer, and used gel-permeation chromotography to show how the degradation occurs principally in the highest molecular weight components of the polymer material.

FLAT PLATES

If polymer drag reduction is to be used in reducing the drag of ships, it will be necessary to have a firm grip on theory and experiment so that performance can be predicted in advance. Recent papers in this area attest to our growing capability in this regard.

Fruman and Tulin [74] tested a 10-ft-long plate with a polymer ejection slot near the leading edge. The tests were conducted at a Reynolds number of 3.5×10^7, and show (figure 10) that drag reductions of over 50 % are readily obtained with ejected polymer, if the ejected concentrations are not so high that a viscous effect occurs. Wu and Tulin [75] show how, on a shorter plate (21 in. long) polymer ejection just sufficient to fill the viscous sublayer results in very appreciable friction reduction, thus confirming again that the near-wall region is the site of the friction-reduction mechanism. Kumor and Sylvester [32] give excellent laser-doppler velocimeter data for boundary-layer flow on a flat plate with and without polymer.

The theoretical maximum drag reduction for a flat plate predicted by Granville [76] found theoretical confirmation both in the more elegant technique of Landweber and Poreh [77] and the simplified approach of McCarthy [78].

Calculations by Poreh and his students [79,80] indicate that the three-zone model of the polymer-filled boundary layer proposed by Virk [81] may be an oversimplification. Virk suggested three regions in the boundary layer: a viscous sublayer; an elastic zone corresponding to the maximum possible drag reduction; and an outer logarithmic zone. Poreh shows how a boundary-layer model based upon a "mixing length" accounts more satisfactorily for data in the buffer or elastic zone; for the flat-plate case the calculations fit the data of Kumor and Sylvester [32] very well indeed. A similar analysis for power-law fluids was given by Hecht [82]. Additional refinements of the boundary-layer model can be expected as better data become available.

THEORIES OF DRAG REDUCTION

Two comprehensive reviews of the status of drag reduction theories appeared recently. A review by Landahl [83] focuses on the fluid dynamics of turbulent flow and how polymer molecules might change the production of turbulence by making the flow more stable. Using as a model elongated particles aligned in the mean-flow direction, Landahl shows how the stream-wise strain could be reduced and thus cause diminished production of turbulent bursts. The evidence for such elongated polymer molecules in the actual flow, however, is not at hand.

Lumley's review [84] centers on the turbulence aspects of polymer flow and how the expansion of random coils of the polymer molecule can reduce the drag. Lumley suggests that the expanded molecular coils decrease the intensity of small eddies; the larger eddies expand and produce an increased stream-wise fluctuating velocity, conforming to the observed laser-doppler measurements.

The trend in the explanation of drag reduction [85–88] centers on the observation that the elongational viscosity (i.e., resistance to stretching) of polymer solutions is very high, while the viscosity measured in the usual way is only nominally changed by the presence of small amounts of polymer. The general concept is that this resistance to stretching interferes with the production of turbulent bursts. This general approach seems to have a high probability for success, since the high elongational viscosity of polymer solutions is easily

demonstrated both analytically and physically, and flow visualization studies have shown the actual reduction of the turbulent bursts in a flowing polymer drag-reducing system.

Other theoretical approaches includes those of Kohn [35] who computed the energy storage capability of polymer molecules and used this with reasonable success to predict the onset of drag reduction in turbulent flow; the Russian work on aggregates or clusters of drag-reducing polymers, and how these aggregates could affect drag reduction [89,90]; the transition stability of polymer solutions [91,92]; and finally, the transition stability of external flows [93].

The explanation of the mechanism of drag reduction still remains the most difficult area of polymer-flow phenomena.

SPECIALIZED TOPICS

In this section several rather diverse topics, which may eventually shed light on the mechanism of the drag-reduction effect or add to our general knowledge of fluid mechanics, are discussed with emphasis on recent papers.

SUSPENSIONS

The study of the flow of drag-reducing suspensions may lead to further insight into the mechanism of polymer-friction reduction, since properly shaped fiber suspensions may model, on a giant scale, the action of polymer molecules in a given flow situation. A rather thorough survey [94] covers the literature through 1971 on the viscosity, viscoelastic, and laminar-flow properties of suspensions. The drag-reducing, turbulent-flow aspects of suspensions are reviewed in [95].

The experimental work reported in [95] shows that several types of asbestos fibers, when properly dispersed in water using a strong surfactant, give excellent drag reductions as shown in figure 11. The asbestos fibrils are extremely long as revealed by photomicrographs (figure 12). Electron micrographs reveal an even finer structure [96]. The study of asbestos fibers as drag-reducing agents was stimulated by the work of Ellis [97], who prepared well-dispersed suspensions and noted high drag-reductions. Since then Peyser [96] and Lee, et al. [98], also confirmed the drag-reducing effectiveness of this material. Solution preparation is the key to good drag-reduction performance, however, since van Driest [99] was unable to show drag reduction in his asbestos suspensions. New methods of opening the asbestos fibrils were reported [100], and these techniques should be explored to study their effect on asbestos suspensions from the drag-reduction standpoint.

Mixtures of drag-reducing polymers and drag-reducing fibers have been studied, with somewhat conflicting results. Bilgen and Boulos [101] showed that under some conditions, mixtures of guar gum and wood pulp give a slight enhancement of the drag-reduction effect, but Lee, et al., [98] reported spectacular friction reduction (89 %) in mixtures of

asbestos and polyacrylamide, and suggested that the drag-reducing effects of polymer and fiber were different and additive. This clearly is an area where intensive study is indicated. It seems from flow studies [102] that the fibers orient themselves with the flow streamlines when in polymer solutions.

The action of polymer solutions on non-drag-reducing suspensions [103,104] is to reduce the drag in about the same proportion as would the same amount of polymer in water alone. Thus Kato, et al., [105] show a large reduction in frictional resistance of a 25 % flyash slurry when 25 ppm of poly(ethylene oxide) is added. Similar results were reported [106] with gravel and polyacryamide solutions.

Suspensions of nylon fibers [107], milling yellow [108], and wood pulp [109] were shown to be drag-reducing compared to water. Moan and Wolff [110] conclude from viscosity measurements that some polymers (i.e., carboxymethylcellulose) behave in solution like suspensions of rigid particles. Thus the action of some polymers and suspensions may actually be similar, a point suggested from the theoretical standpoint by McComb [111].

The large friction reductions available through the use of particle suspensions in liquids make it certain that industrial utilization of the effect will eventually assume an important role. Since particulate matter can easily be added (and more importantly, be removed) from flowing systems, and the problem of degradation or loss of effectiveness so prevalent in polymer friction-reducing additives seems of no concern with rigid particles, the way appears clear to capitalize on applications of the effect. A complete understanding of the fluid dynamics involved in particle-suspension flow, however, still seems remote.

HEAT TRANSFER

Closely related to friction reduction is the topic of heat transfer in polymer solutions. Heat transfer data may shed additional light on the complex phenomena occurring in the flow of drag-reducing fluids. No adequate review of the background in this area is available and hence a brief mention of earlier work seems valuable before discussing the current papers.

The heat-transfer measurements of Pruitt, et al., [112] appear to be the earliest as well as the most comprehensive. The heat-transfer coefficients for polyacrylamide and carboxymethylcellulose were measured in a 1/2-in.-I.D. aluminum pipe with 1/8-in.-thick walls, at various flow rates. They found the heat transfer coefficient to be greatly depressed by the presence of macromolecules. This could be expected on the basis of the thickened sublayer and diminished turbulence intensity that previously was shown to play an important role in the flow of polymer solutions.

Wells [113] and Poreh and Paz [114] further analyzed the data of Pruitt, et al., to cast the results into a form more amenable for production.

Poreh and Paz were able to correlate within ±20 % not only all the data on Pruitt, et al., but also additional guar data of their own, and data on a different polyacrylamide from the thesis of Gupta [115, 116].

12

From a further analysis of Wells' work, D. A. White [117] concludes that adding polymers to a solvent always gives a reduction of heat transfer, even though the fluid velocity may be increased due to friction reduction.

Additional experimental data [118] is available for guar solutions in a 0.92-in.-I.D. pipe. The reduction in heat transfer when high-polymer substances are present in the fluid was found to be even larger than the reduction in friction coefficient – another indication of the powerful change in fluid properties produced by macromolecules.

The papers both of Wells and of Poreh and Paz note that the laminar heat transfer in these dilute polymer solutions is the same as water, as would be expected since the frictional properties would be unchanged from the solvent in laminar flow.

Marrucci and Astarita [119] presented additional heat transfer data in a different form. Using the polyacrylamide ET 597 at 600 ppm, they found the reduction in heat transfer compared with water to be lower than predicted by the Colburn relationship often used with Newtonian fluids. The Colburn "j" is:

$$j_q = \frac{f}{2} = (St)\,(Pr)^{2/3}$$

Marrucci and Astarita found that $(St)(Pr)^{2/3}$ was significantly lower than $f/2$ for this strongly friction-reducing fluid. These data were taken in a 12-cm-I.D. pipe. Thus it was found that the reduction in heat transfer accompanying friction-reduction flow is an important characteristic of polymer solutions.

Later it was found that the Colburn analogy, $j_q = f/2$, could be applied, provided a Reynolds number shift is made that essentially matches the onset Reynolds number for friction reduction with the "onset" Reynolds number for heat-transfer reduction. The difference in these Reynolds numbers was a factor of about 3 for poly(ethylene oxide); onset of the heat transfer occurring later.

However, Smith, et al., [120] also found it possible to use the Colburn analogy in their study of heat-transfer to poly(ethylene oxide) solutions. In the laminar flow regime, no difference was observed from ordinary Newtonian fluid heat-transfer characteristics for the polymer solutions. For turbulent flow the following relationships were found:

Maximum friction reduction: $f/2 = 0.21\,Re^{-0.54}$

Maximum heat-transfer reduction: $(St)(Pr)^{0.6} = 0.184\,Re^{-0.54}$

Thus it appears that, for the <u>maximum</u> conditions of friction- and heat-transfer-reduction due to polymer additives, the Colburn analogy is a useful relationship.

In the case of very rough pipe, A. White [121] found that poly(ethylene oxide) solutions again produce a reduction in heat transfer, this reduction becoming more pronounced as the Reynolds number is increased. White showed that with the poly(ethylene oxide) less heat is carried away by a greater flow of solution than a lesser flow. Evidently much more work will be needed for a full understanding of these effects, since White asserts that guar gum solutions give similar results to water in the roughened pipe.

Further analyses of the heat-transfer/drag-reduction case were done by Meek and Baer [122], Rubin [123], and Hughmark [124]. Additional heat-transfer data are given in [125-127]. The most comprehensive study to date is that of Debrule [128], who measured both drag reduction and heat transfer in a series of smooth and well-characterized rough pipes. Debrule found drag reductions as high as 73 % in smooth tubes, and 83 % in rough tubes, with poly(ethylene oxide). This friction reduction was accompanied by an even larger decrease in heat transfer. The heat transfer in rough tubes is reduced so drastically (figure 13) that in some ranges the heat-transfer coefficients with poly(ethylene oxide) appears to be lower in rough tubes than in smooth tubes.

The tremendous reduction of heat transfer accompanying the reduction of friction by poly(ethylene oxide) and other polymers may suggest their use in specialized applications such as the pipeline transport of oil through cold areas, where good friction reduction and low heat loss would be an advantage.

NOISE

Another manifestation of the changed flow characteristics of polymer solutions compared with water is the change in radiated noise from the boundary layer when polymers are present. This type of measurement might give an indication that the turbulent intensities are diminished in drag-reduced flows. The experimental technique required, and the sophistication of the noise measurements and the data processing make this a difficult field in which to work. Recently, however, several important studies in this area have been reported.

Killen [129] measured the radiated noise from a rotating, rough-surface cylinder in a large water tank with and without polymer, and found that the radiated flow noise was reduced approximately 10 dB when 100 ppm of poly(ethylene oxide) was added to the tank. Brady [130] performed a similar experiment and also noted a reduction of 10 dB or more radiated noise with polymer addition.

An even more sophisticated experiment by Barker [131] used a rotating spiral of sheet steel, arranged to give a continuously renewing boundary layer on the surface of the plate. Both the fluctuating wall-pressures and the noise radiated from the boundary layer were measured. The wall-pressure spectra were reduced about 9 dB in the higher frequencies, and the radiated noise was also reduced a similar amount. As shown in figure 14, above 1 kHz a substantial reduction in radiated flow noise occurs when 100-ppm poly(ethylene oxide) is introduced into the flow. Barker suggests that these results are another indication of the suppression of turbulent bursts in the boundary layer. Additional work in this area is certain to increase our insight as to the mechanisms at play in the flow of polymer fluids.

CAVITATION

Still another aspect of polymer flow is the discovery that drag-reducing macromolecules inhibit the inception of cavitation in a given flow situation. Cavitation is the sudden formation of vapor bubbles in the fluid, analogous to boiling.

Ellis [132, 133] conducted a series of experiments to explore the effect of high-polymer substances on both cavitation inception and appearance.

Cavitation inception was studied on a hemisphere-nosed cylindrical body in a flow-down water tunnel. Using a 0.635-cm-diameter stainless steel test body, the inception of cavitation was detected in two ways. A laser beam was adjusted to just graze the surface of the hemisphere nose in the region where cavitation first appears. Light scattered by the cavitation bubbles was detected by a photocell sensing light at about 90° from the laser beam direction. This method of cavitation detection was checked by acoustic observation, and extremely close agreement was obtained.

Tests were made with water (passed through an 0.4-μ filter), 50- and 100-ppm poly(ethylene oxide), and a suspension of alga, *Porphyridium aerugineum.*

All tests were made with water containing the same amount of dissolved air, at 17-ppm.

The cavitation inception index, σ_i, is defined by

$$\sigma_i = \frac{P_i - P_v}{1/2\,\rho\,V^2}$$

where P_i is the static pressure at cavitation inception, P_v the vapor pressure of water, ρ the water density and V the flow velocity.

The following inception data were obtained (averages of 4 runs):

	Tunnel Velocity (m/s)	Inception Cavitation Index
Water	12.55	0.73
20-ppm poly(ethylene oxide)	13.40	0.50
50-ppm poly(ethylene oxide)	14.18	0.39
100-ppm poly(ethylene oxide)	13.70	0.41
Algae	12.88	0.66

Thus, it can be seen that the polymer content of the water has a large effect on the cavitation inception point. This may be a factor in explaining the large differences in inception index found in tests of the same body shape in water tunnels throughout the world [134], since unknown amounts of algal or bacterial polymer might be present in the water.

The initial appearance of the cavitation bubble is also changed by the presence of dissolved high polymer. There also seems to be a noticeable difference [135] in the appearance of steady-state cavities in flows containing high-polymer solutions compared with observations at the same cavitation index in pure water. The polymer solution cavity is more striated, and appears to collapse less violently than the water cavity; high frequency-response pressure measurements confirm the diminishing of the intensity of fluctuations. Thus, a change in external appearance of cavitation may be expected when known (or unknown) contamination of the water tunnel by high-polymer substances occurs.

The changed appearance of cavities in polymer fluid flow as compared with pure water is beautifully shown by the photographs of Brennen [136], who studied the flow over cavitating hemispherical head shapes. Brennen found that all polymers tested (poly(ethylene oxide), guar, polyacrylamide, and CTAB-napthol) had pronounced effects on cavity appearance. There is as yet no explanation for these changes in the flow behavior.

Recent cavitation studies in polymer solutions centered on jet cavitation, cavitation inception on rotating disks and propellers, and water tunnel studies of hemispherically nosed shapes. Jet cavitation studies [137, 138] show that the cavitation index can be reduced to half the previous value when small quantities of poly(ethylene oxide) are present in the flow; amounts as small as 1/2 ppm were detectable by this technique. Figure 15 shows the observed cavitation index as a function of polymer concentration; this effect is all the more remarkable when one considers that the surface tension is also drastically lowered by these polymers.

Walters [139] showed a similar lowering of cavitation inception index on a disk, and J. R. White [140] found that the cavitation bubble production by a small propeller, observed by counting bubble collapses, was greatly reduced by 25 ppm or more poly(ethylene oxide). Both Walters and White noted that the higher-frequency noise content (5-15 khz) of the bubble collapse spectra was diminished. Under very intense cavitation, the polymer solution produced a higher level of radiated noise at high frequencies than water. Acoustically produced cavitation inception was also retarded by the presence of polymer.

van der Meulen [141] showed that cavitation inception on a hemispherical-nosed stainless steel body in a water tunnel is greatly reduced by the presence of poly(ethylene oxide), while a teflon-coated body showed a much smaller effect. In other work, Huang [142] noted that the cavitation inception reduction with poly(ethylene oxide) was much smaller when a large (4-inch diameter) model was used in a water tunnel. No theoretical approach to cavitation in polymer solutions has been offered except briefly in a note by Lumley [143].

Cavitation in polymer solutions is a most fertile field for new advances in our study of macromolecular flow, since research may shed new light on the old problems of Newtonian fluid cavitation, and also since the potential applications of cavitation reduction are many.

JET FLOW OF POLYMER SOLUTIONS

The effort to secure a new approach to polymer solution properties in order to illuminate still another facet of the drag-reduction problem has led experimenters to several novel studies. Often these new approaches, rather than solving the original problem, created new questions. New fields for research thus have opened up at a rapid rate as the polymer solution properties are further explored. This has been especially true for jets.

16

Striking changes occur in the visual appearance of a jet of water discharging into air when small amounts of a high polymer such as poly(ethylene oxide) are added to the flow. This occurs in laminar, transitional, and turbulent jet flow.

Fascinating photographs of the breakup of laminar-flow jets of water and polymer solutions were taken by Shinnar and his students [144,145], and theoretical analyses were published [146,147] confirming that the addition of polymer destabilizes the laminar jet and causes it to break up earlier than the corresponding Newtonian case. Similar earlier instabilities occur in the transitional laminar-turbulent case [148].

More intensive work has been done on turbulent jets. Jackley [149] studied the velocity distribution in a small jet of polyacrylamide discharged into a tank of the same fluid. The results of the experiment showed that the nondimensionalized velocity profile across the jet was indistinguishable from that of water. He found, however, that the pressure in the jet at the nozzle centerline was less with polyacrylamide solutions than with water and attributed this to the polymer solution having less total momentum. D. A. White [150] performed an almost identical experiment using as polymer, hydroxyethyl cellulose, guar, and poly(ethylene oxide). White found that while the polymers, guar, and hydroxyethyl cellulose gave the same results for centerline pressure and velocity distribution as water, the centerline velocity for a 100-ppm solution of poly(ethylene oxide) was much lower than that of water.

Pownall and Kiser have interpreted similar measurements [151] as due to the viscoelastic expansion of synthetic polymer fluids as they leave the nozzle (i.e., the "die swell" effect). Due to expansion on leaving the nozzle, the centerline velocity is quickly reduced compared to Newtonian fluids, and this result appears in the velocity survey measurement. The approach of Pownall and Kiser explains the apparent anomaly of the measurements reported in the literature, but "die swell" has never been seen in turbulent jets of viscoelastic liquids in air.

Gadd [152,153] observed dyed fluid jets that were originally laminar but turned turbulent after leaving the nozzle. Gadd found large differences between the appearance of a water jet and a jet containing 30-ppm poly(ethylene oxide), each jet discharging into a tank of the same fluid. Gadd's pictures indicate that the smaller turbulent eddies are not found in poly(ethylene oxide) jets. Surprisingly, jets of other polymers (such as guar), having equivalent friction-reducing ability in turbulent pipe flow, had the same appearance in the jet experiments as water.

Goren and Norbury [154] found that the velocity profiles of a turbulent jet containing 50-ppm poly(ethylene oxide) when discharging into water were identical to those of a water jet. The photographs of A. White [155] clearly show a marked difference between a 50-ppm poly(ethylene oxide) jet (discharging into a poly[ethylene oxide] solution) compared with a similar water jet discharging into water. Wu [156] found that the appearance of a jet discharged into a water stream flowing behind a turbulence grid was markedly changed when poly(ethylene oxide) was added to the jet.

Barker [157], using a laser-doppler velocimeter, showed there is no discernable difference in gross structure (i.e., centerline velocity, velocity profile, etc.) between water and poly(ethylene oxide) solution jets discharging under water. A small difference was observed using guar solutions [158]. On the other hand, a large decrease in cavitation-inception parameter in jets discharged under water was found when polymers were present in the fluid. Further, addition

of polymers seems to improve the ability of high-speed jets to act as cutting tools both in air [159] and under water [160]. Turbulent diffusion of heat is affected in polymer jets [161].

Clearly the addition of polymers to turbulent fluid-jet discharges cause a change in the flow as evidenced by photography and cavitation inception, but this change is almost undetectable with the usual flow instrumentation, which measures average properties of the flow. In order to shed more light on this problem, a special camera was developed for jet photography, and the jet appearance was recorded as a function of polymer concentration and of distance from nozzle. The results [162] show profound differences in the surface appearance of the jet as it is discharged from the nozzle, as it travels through the air, and as it breaks up into spray, when polymers are present in the flow.

Figure 16 shows photographs of jets of water and 200-ppm poly(ethylene oxide) as they leave the nozzle, discharging into air, and figure 17 shows the break-up of these jets.

These interesting results make it imperative that further study be made of the nature of the turbulent-jet boundary interactions when polymer molecules are present in the fluid. The large differences between polymers (and between experiments) make it clear that there is much to be learned by a more thorough study of the jet boundary interactions. Although it was first thought that the presence of a wall or fixed boundary was necessary for friction-reducing polymers to influence turbulent flow phenomena, it appears that for some polymers at least, this is not necessary.

THE EFFECT OF POLYMERS ON LIFT

An even more mystifying (more so than drag reduction itself) effect of dilute high-polymer solution flows is the possibility that the lift produced by hydrofoil sections can be reduced in such flows. Wu [163] noted that the thrust of the impeller of a small water tunnel seemed to decrease when polymer was present in the flow; after a given recirculation time the thrust returned to normal, which Wu attributed to degradation. The initial effect, inferred from impeller thrust measurements, amounted to a few percent at 10-ppm poly-(ethylene oxide), to 50 % reduction with 500 ppm.

Kowalski [164] tested a small propeller in a recirculating channel and found that the thrust was reduced slightly and the torque at a given speed increased, giving a net reduction in efficiency of about 5 %.

A slightly clearer picture of what might be occurring is gained from the experiments of Kilian [165]. A transparent plastic propeller having a diameter of 22 cm was designed from an uncambered NACA 0009 airfoil profile so that there is no thrust produced by the propeller. Test data were taken on this "propeller" in 50- to 100-ppm poly(ethylene oxide) and in a 3 % glycerine solution having the same viscosity as the polymer solutions. At low rotative speeds, tests in the polymer solution required more torque, but at higher speeds there was a small drag reduction. In contrast, a rotating disk of the same diameter showed a large drag reduction in polymer solutions. The reduced effectiveness of drag-reducing polymers on the propeller may be indicative of the viscoelastic stresses in the liquid at the leading and trailing edges of the hydrofoil. Kilian further showed that a very poor propeller became worse in polymer solutions [166].

18

Tests on a cavitating hydrofoil showed a large reduction of lift with only 1 ppm of poly(ethylene oxide) present in the test water. Sarpkaya [167] also noted a reduction of lift on a NACA 0024 hydrofoil when 1 ppm of poly(ethylene oxide) was added to a small water tunnel. Kawada and Tagori [168] also found a reduction in lift in polymer solutions, and proceeded by means of detailed pressure-distribution measurements and bubble-streak photographs, to show that the lift reduction is caused by leading-edge separation, followed by longitudinal vortices shed over the suction surface of the hydrofoil. Figure 18 shows some of the pressure distributions obtained by Kawada and Tagori, and figure 19 shows one of the bubble-streak photographs.

By ejecting polymer solutions from slots in the suction and pressure surfaces on a small airfoil in a water tunnel, Lehman and Suessmann [169] found that the lift could be either increased or decreased as a function of the test parameters. With no ejection, and using homogenous solutions of poly(ethylene oxide) of up to 17 ppm in all the fluid of the water tunnel, Lehman and Suessmann found a slight (5 %) *increase* in lift and a large decrease in drag.

The lift reduction found in the laboratory is surprising since no problems were noted in full-scale ship trials [170]. Sanders and his students [171, 172] also found no effect of polymer on performance of a small propeller. Recent unpublished data (figure 20) taken in a large water tunnel at the Applied Research Laboratory at Pennsylvania State University also indicate the open water performance of a propeller is unaffected by polymer. However, a propeller designed to operate in the wake of a cylindrically shaped body did suffer about 10 % performance degradation in polymer solutions.

It can be expected that the lift problems in polymer solutions will be solved by increased knowledge, special hydrofoil designs, and attention to inflow conditions.

Since changes in propeller performance are of intense practical interest in the application of polymers to pumping machinery and ships, it can be expected that a large amount of effort will be concentrated on this facet of polymer solution flows in order to provide a more satisfying explanation of the observed experimental results.

SUMMARY

In summary, many new scientific and technological advances have already been accomplished and many more will undoubtedly come forth in the future through the study of the flow of high-polymer solutions. The implications of this progress for future Navy applications are that many tangible benefits can be expected. In particular, application of drag-reducing polymers to fire-fighting at Navy installations and on ships should greatly improve effectiveness by increasing water-flow rates and providing more coherent jets of water. Military applications of drag reduction for short-duration, high-speed bursts on specialized vehicles should be considered. Finally the medical applications can become highly useful to people everywhere.

REFERENCES

1. J. W. Hoyt. The Effect of Additives on Fluid Friction. *J. Basic Engineering, Trans. ASME, 94, D,* 1972, p. 258.

2. K. J. Mysels. Early Experiences with Viscous Drag Reduction. *Chemical Engineering Progress, Symposium Series, 67,* No. 111, 1971, p. 45.

3. Engineering Research Center, Colorado State University. Viscous Drag Reduction in Developing Pipe Flow, by J. P. Tullis, K. L. V. Ramu, Hydro Machinery Laboratory Report No. 34, 1973.

4. J. V. Kelkar, R. A. Mashelkar. Drag Reduction in Dilute Polymer Solutions. *J. Applied Polymer Science 16,* 1972, p. 3047.

5. H. Rubin, C. Elata. Turbulent Flow of Dilute Polymer Solutions Through an Annulus. *AIChE Journal 17,* 1971, p. 990.

6. E. J. Greskovich, A. L. Shrier. Drag Reduction in Two-Phase Flows. *Ind. Eng. Chem. Fundamentals 10,* 1971, p. 646.

7. C. A. Parker, A. H. Hedley. Drag Reduction and Molecular Structure. *Nature—Physical Science 236,* 1972, p. 61.

8. Admiralty Research Laboratory, Teddington, England. The Effect of Temperature on Drag Reduction Effectiveness of Polyox and of Polyacrylamide, by E. W. A Pike. Report ARL/C/N°, 1971.

9. W. D. White. Drag-Reduction Measurements for Three Polymers at 4° C. *Viscous Drag Reduction,* C. S. Wells, ed., Plenum Press, N. Y., 1969, p. 173.

10. R. Y. Ting, O. -K. King. Drag-Reduction Properties of Ultra-High-Molecular-Weight Polyacrylamide and Related Polymers. *Water Soluble Polymers,* N. M. Bikales, Plenum Press, N. Y. 1973, p. 151.

11. I. T. El'perin, L. Z. Mel'tser, L. I. Levental', V. S. Kovalenko, V. L. Met'tser. The Influence of High-Molecular-Weight Additives on the Flow of a Viscous Liquid. *Fluid Mechanics-Soviet Research 2,* No. 1, 1973, p. 115.

12. Admiralty Mat- rials Laboratory, Holton Heath, England. An Investigation into the Drag Reducing Properties of Plant Polysaccharides, by H. G. Stebbins. Report No. 19/72, 1972.

13. J. W. Hoyt. Drag-Reduction Effectiveness of Polymer Solutions in the Turbulent-Flow Rheometer: A Catalog. *Polymer Letters 9*, 1971, p. 851.

14. J. L. Zakin, J. L. Chiang. Non-Ionic Surfactants as Drag Reducing Additives. *Nature—Physical Science 239*, 1972, p. 26.

15. J. L. Zakin. Effect of Age and Water Content on Drag Reduction in Aluminum Disoap-Hydrocarbon Solutions. *Nature—Physical Science 235*, 1972, p. 97.

16. B. C. Ramakrishnan, F. Rodriguez. Drag Reduction in Non-Aqueous Liquids. *AIChE Symposium Series, 69*, No. 130, 1973, p. 52.

17. R. H. Wade. The Pollution Potential of Drag Reducing Polymers. *AIChE Symposium Series, 69*, No. 130, 1973, p. 87.

18. N. S. Berman, G. B. Gurney, W. K. George. Pitot tube errors in dilute polymer solutions. *Physics of Fluids 16*, 1973, p. 1526.

19. J. M. Rodriguez, G. K. Patterson, J. L. Zakin. Measurement of Turbulence Intensities with Piezoelectric Probes in Viscoelastic Fluids. *J. Hydronautics 5*, 1971, p. 101.

20. G. L. Donohue, W. G. Tiederman, M. M. Reischman. Flow Visualization of the Near-Wall Region in a Drag-Reducing Channel Flow. *J. Fluid Mechanics 56*, 1972, p. 559.

21. G. Fortuna, T. J. Hanratty. The Influence of Drag-Reducing Polymers on Turbulence in the Viscous Sublayer. *J. Fluid Mechanics 53*, 1972, p. 575.

22. L. D. Eckelman, G. Fortuna, T. J. Hanratty. Drag Reduction and the Wavelength of Flow-oriented Wall Eddies. *Nature- Physical Science 236*, 1972, p. 94.

23. A. White. Velocity Profiles of a Complex Soap System in Turbulent Pipe Flow. *Nature—Physical Science 235*, 1972, p. 154.

24. A. Rollin, F. A. Seyer. Velocity Measurements in Turbulent Flow of Viscoelastic Solutions. *Canadian J. Chem. Engrg 50*, 1972, p. 714.

25. C. Gebel, H. Reitzer. Étude de la couche limite hydrodynamique. Écoulement autor d'un cylindre avec injection pariétale de fluide non-newtonian. *C. R. Acad. Sc. 275*, A, Paris, 1971, p. 1175.

26. Vr. Arunachalam, R. L. Hummel, J. W. Smith. Flow Visualization Studies of a Turbulent Drag Reducing Solution. *Canadian J. Chem. Engrg. 50*, 1972, p. 337.

27. M. J. Rudd. Laser Dopplermeter and Polymer Drag Reduction. *Chemical Engrg Progress, Symposium Series 67*, No. 111, 1971, p. 21.

28. ——————. Velocity measurements made with a Laser Dopplermeter on the Turbulent Pipe Flow of a Dilute Polymer Solution. *J. Fluid Mech. 51*, 1972, p. 673.

29. J. S. Chung, W. P. Graebel. Laser Anemometer Measurements of Turbulence in Non-Newtonian Pipe Flows. *Physics of Fluids 15*, 1972, p. 546.

30. M. M. Reischman. *Laser Anemometer Measurements in Drag-Reducing Channel Flows.* PhD Thesis, Oklahoma State University, 1973.

31. S. E. Logan. Laser Velocimeter Measurement of Reynolds Stress and Turbulence in Dilute Polymer Solutions. *AIAA Journal 10*, 1972, p. 962.

32. S. M. Kumor, N. D. Sylvester. Effects of a Drag-Reducing Polymer on the Turbulent Boundary Layer. *AIChE Symposium Series 69*, No. 130, 1973, p. 1.

33. Ya. I. Voitkounsky, W. R. Amfilokhiev, V. A. Pavlovsky. On the Theoretical Description of the Flows of Dilute Polymer Solutions. Paper distributed on the occasion of the ONR Ninth Symposium on Naval Hydrodynamics, Paris, 1972.

34. R. J. Hansen. The Reduced Drag of Polymer Solutions in Turbulent and Transient Laminar Shear Flows. *J. Fluids Engineering, Trans. ASME 1*, p. 23.

35. M. C. Kohn. Energy Storage in Drag-Reducing Polymer Solutions. *J. Polymer Science 11*, 1973, p. 2339.

36. J. W. Hoyt. Blood Transfusion Fluids Having Reduced Turbulent Friction Properties. U. S. Patent 3,590,124, 1971.

37. W. E. Castro, J. G. Neuworth, Jr. Reducing fluid friction with Okra. *Chem Tech 1*, *1971*, p. 697.

38. Water Resources Research Institute, Clemson University. Reduction of Flow Friction with Polymer Additives, by W. E. Castro. Report No 24, 1972.

39. R. L. Dooley, B. W. Sauer, W. E. Castro. Drag Reduction in Prosthetic Heart Valves using High Polymer Additives. *Proceedings 25th Annual Conference on Engineering in Medicine and Biology*, 1972, p. 350.

40. H. L. Greene, R. F. Nokes, L. C. Thomas. Drag Reduction Phenomena in Pulsed Blood Flow. *Symposium on Flow, Pittsburg, 1971*, paper 4-4-64.

41. L. C. Thomas, H. C. Greene, R. F. Nokes, M. Chu. Turbulence Studies of Steady and Pulsed Flow of Drag Reducing Solutions. *AIChE Symposium Series 69*, No. 130, 1973, p. 14.

42. R. R. Walters, C. S. Wells, Jr. Effects of Distributed Injection of Polymer Solutions on Turbulent Diffusion. *J. Hydronautics 6*, 1972, p. 69.

43. M. Poreh, R. S. Ksu. Diffusion of Drag Reducing Polymers in a Turbulent Boundary Layer. *J. Hydronautics 6*, 1972, p. 27.

44. J. Wu. Suppressed Diffusion of Drag-Reducing Polymer in a Turbulent Boundary Layer. *J. Hydronautics 6*, 1972, p. 46.

45. —————— ————. An Experiment on Turbulent Diffusion in Additive Solutions. *AIChE Journal 17*, 1971, p. 1408.

46. A. W. Bryson, Vr. Arunachalam, G. D. Fulford. A Tracer Dispersion Study of the Drag-Reduction Effect on a Turbulent Pipe Flow. *J. Fluid Mech. 47*, 1971, p. 209.

47. J. P. Peterson. Increased Turbulent Dispersion in Dilute High Polymer Drag Reducing Open Channel Flow. PhD Thesis, Clemson University, 1972.

48. P. R. Kenis. Turbulent Flow Friction Reduction Effectiveness and Hydrodynamic Degradation of Polysaccharides and Synthetic Polymers. *J. Applied Polymer Science 15*, 1971, p. 607.

49. D. H. Fisher, R. Rodriguez. Degradation of Drag-Reducing Polymers. *J. Applied Polymer Science 15*, 1971, 2975.

50. N. D. Sylvester, S. M. Kumor. Degradation of Dilute Polymer Solutions in Turbulent Tube Flow. *AIChE Symposium Series 69*, No. 130, 1973.

51. A. T. Ellis, R. Y. Ting, R. H. Nadolink. Some Storage and Shear History Effects on Polymeric Friction Reduction. *J. Hydronautics 6*, 1972, p. 66.

52. B. J. S. Barnard, R. H. J. Sellin. Degradation of Dilute Solutions of Drag-reducing Polymer. *Nature - Physical Science 236*, 1972, p. 12.

53. R. Y. Ting, R. C. Little. Shear Stability of Drag-reducing Polyacrylic Acid Solutions. *Nature — Physical Science 241*, 1973, p. 42.

54. —————— ————. Characterization of Drag Reduction and Degradation Effects in the Turbulent Pipe Flow of Dilute Polymer Solutions. *J. Applied Polymer Science 17*, 1973, p. 3345.

55. J. H. T. Wade, P. Kumar. Electron Microscope Studies of Polymer Degradation. *J. Hydronautics 6*, 1972, p. 40.

56. H. Kato, K. Watanabe, K. Ueda. Frictional Resistance of Rotating Disk in Dilute Polymer Solutions — Part 1, Enclosed Disk. *Bulletin JSME 15*, 1972, p. 1185.

57. E. A. Bilgen. On the Stability of Viscoelastic Flow due to a Rotating Disk. *Chemical Engineering Progress, Symposium Series, 67*, No. 111, 1971, p. 74.

58. E. Bilgen, P. Vasseur. On the Friction Reducing Non-Newtonian Flow Around an Enclosed Disk. *ASME Preprint 73-APM-GG, 1972*

59. E. Bilgen. Sealing Properties of Dilute Polymer Solutions. *Proc. Fifth International Conference on Fluid Sealing, Warwick, 1971*, p. 53.

60. E. Bilgen, R. Boulos. Turbulent Flow of Drag Reducing Fluids between Concentric Rotating Cylinders. *CSME Trans. 1,* 1972, p. 25.

61. P. Peyser, R. C. Little. The Drag Reduction of Dilute Polymer Solutions as a Function of Solvent Power, Viscosity and Temperature. *J. Applied Polymer Science 15,* 1971, p. 2623.

62. D. D. Kale, R. A. Mashelkar, J. Ulbrecht. Drag Reduction in Rotational Viscoelastic Boundary Layer Flows. *Nature – Physical Science 242,* 1973, p. 29.

63. Y. Tomita, Y. Mochimaru. A Study on the Flows of Dilute Polymer Solutions. (First Report, Frictional Resistance of a Rotating Disk in a Dilute Polymer Solution.) *Bulletin JSME 16,* 1973, p. 291.

64. P. S. Granville. The Torque and Turbulent Boundary Layer of Rotating Disks with Smooth and Rough Surfaces, and in Drag-Reducing Polymer Solutions. *J. Ship Research 17,* 1973, p. 181.

65. R. A. Mashelkar. Drag Reduction in External Rotational Flows. *AIChE Journal 19,* 1973, p. 382.

66. C. Wang. Correlation of the Friction Factor for Turbulent Pipe Flow of Dilute Polymer Solutions. *Ind. Eng. Chem. Fundamentals 11,* 1972, p. 546.

67. G. Fortuna, T. J. Hanratty. Use of Electrochemical Techniques to Study the Effect of Drag-Reducing Polymers on Flow in the Viscous Sublayer. *Chemical Engrg Progress, Symposium Series, 67,* No. 111, 1971, p. 90.

68. G. A. Sidahmed, R. G. Griskey. Mass Transfer in Drag Reducing Fluid Systems. *AIChE Journal 18,* 1972, p. 138.

69. R. Greif, I. Cornet, R. Kappesser. Diffusivity of Oxygen in a Non-Newtonian Saline Solution. *Int. J. Heat Mass Transfer 15,* 1972, p. 593.

70. C. Deslouis M. Keddam. Emploi d'électrodes a anneau tournant a l'étude du transport de matière dans un fluide en régime hydrodynamique laminaire ou turbulent. *Int. J. Heat Mass Transfer 16,* 1973, p. 1763.

71. C. Deslouis, I. Epelboin, B. Tribollet, L. Viet. Étude du transport de matière dans un électrolyte à la surface d'une électrode tournante à disque ou à anneau en présence d'un haut polymère. *C. R. Acad. Sc. 277, C,* Paris 1973, p. 353.

72. P. I. Gold, P. K. Amar, B. E. Swaidan. Friction Reduction Degradation in Dilute Poly(ethylene oxide) Solution. *J. Applied Polymer Science 17,* 1973, p. 333.

73. A. H. Abdel-Alim, A. E. Hamielec. Shear Degradation of Water-Soluble Polymers. I. Degradation of Polyacrylamide in a High-Shear Couette Viscometer. *J. Applied Polymer Science 17,* 1973, p. 3769.

74. Hydronautics, Inc. Drag Reduction and Diffusion Accompanying Thin Slit Injections of a Drag Reducing Polymer on a Flat Plate at High Reynolds Numbers, by D. H. Fruman, M. P. Tulin. Technical Report 7101-3, 1972.

75. J. Wu, M. P. Tulin. Drag Reduction by Ejecting Additive Solutions into Pure-Water Boundary Layer. *J. Basic Engineering Trans ASME 94D,* 1972, p. 749.

76. P. S. Granville. Maximum Drag Reduction for a Flat Plate in Polymer Solutions. *J. Hydronautics 6,* 1972, p. 58.

77. L. Landweber, M. Poreh. Frictional Resistance of Flat Plates in Dilute Polymer Solutions. *J. Ship Research 17,* 1973, p. 227.

78. J. H. McCarthy. Flat-Plate Frictional-Drag Reduction with Polymer Injection. *J. Ship Research 15,* 1971, p. 278.

79. Technion, Haifa. Velocity Distribution and Friction Factors in Pipe Flows with Drag Reduction, by M. Poreh, Y. Dimant. Faculty of Civil Engineering Publication 175, 1972. Also in *Proc. 9th Symposium on Naval Hydrodynamics, Paris, 1972.*

80. ————————. Phenomenological Models of Boundary Layer Flows with Drag Reuction, by M. Poreh, L. Grunblatt. Faculty of Civil Engineering Publication No. 196, 1973.

81. P. S. Virk. An Elastic Sublayer Model for Drag Reduction by Dilute Solutions of Linear Macromolecules. *J. Fluid Mechanics 45,* 1971, p. 417.

82. A. M. Hecht. A Turbulent Mixing Length Formulation for Non-Newtonian Power Law Fluids. *J. Hydronautics 6,* 1972, p. 21.

83. M. T. Landahl. Drag Reduction by Polymer Addition. *Proc. XIII International Congress of Theoretical and Applied Mechanics, Moscow, 1972.*

84. J. L. Lumley. Drag Reduction in Turbulent Flow by Polymer Additives. *Macromolecular Reviews 7,* 1973, p. 263.

85. E. Ruckenstein. On the Mechanism of Drag Reduction in Turbulent Flow of Visco-elastic Liquids. *Chemical Engineering Science 26*, 1971, p. 1075.

86. A. E. Everage, Jr., R. J. Gordon. On the Stretching of Dilute Polymer Solutions. *AIChE Journal 17*, 1971, p. 1257.

87. R. Y. Ting. On the Mechanisms for Drag Reduction: A Viscoelastic Evaluation Based on a Bead-Spring Model. *J. Applied Polymer Science 16*, 1972, p. 3169.

88. E. Ruckenstein. A Note on the Mechanism of Drag Reduction, *J. Applied Polymer Science 17*, 1973, p. 3239.

89. V. N. Kalashnikov, A. M. Kudin. Size and Volume Concentration of Aggregates in Drag-reducing Polymer Solutions. *Nature – Physical Science 242*, 1973, p. 92.

90. A. M. Kudin. On the Size of Molecular Clusters Reducing Hydrodynamic Drag in Polymer Solutions. *Fluid Mechanics-Soviet Research 2*, No. 5, 1973, p. 112.

91. P. C. Forane, R. J. Hansen, R. C. Little. Observations of Early Turbulence in the Pipe Flow of Drag Reducing Polymer Solutions. *AIChE Journal 18*, 1972, p. 213.

92. R. J. Hansen. Stability of Laminar Pipe Flows of Drag Reducing Polymer Solutions in the Presence of High-Phase-Velocity Disturbances. *AIChE Journal 19*, 1973, p. 298.

93. W. C. Rivard, E. S. Kulinski. Nonuniform Concentration – A Mechanism for Drag Reduction. *Physics of Fluids 15*, 1972, p. 728.

94. R. G. Cox, S. G. Mason. Suspended Particles in Fluid Flow through Tubes. *Annual Reviews of Fluid Mechanics 3*, 1971, p. 291.

95. Naval Undersea Center. Turbulent Flow of Drag-Reducing Suspensions, by J. W. Hoyt. Technical Report NUC TP 299, 1972.

96. P. Peyser. The Drag Reduction of Chrysotile Asbestos Dispersions. *J. Applied Polymer Science 17*, 1973, p. 421.

97. H. D. Ellis. Effects of Shear Treatment on Drag-reducing Polymer Solutions and Fibre Suspensions. *Nature 226*, 1970, p. 352.

98. W. K. Lee, R. C. Vasceleski, A. B. Metzner. Turbulent Drag Reduction in Polymeric Solutions Containing Suspended Fibers. *AIChE Journal 20*, 1974, p. 128.

99. E. R. van Driest. Turbulent Flow of Non-Newtonian Fluids. *Proc. 9th International Symposium on Space Technology and Science, Tokyo, 1971*, p. 349.

100. M. Xanthos, R. T. Woodhams. Polymer Encapsulation of Colloidal Asbestos Fibrils. *J. Applied Polymer Science 16*, 1972, p. 381.

101. E. Bilgen, R. Boulos. Friction Reduction by Chemical Additives in the Turbulent Flow of Fibre Suspensions. *Canadian J. of Chem. Engr. 51*, 1973, p. 405.

102. L. Nicodemo, L. Nicolais, D. Acierno. Orientation of Short Fibers in Polymer Materials resulting from Converging Flow. *Quaderni dell' Ingegnere Chimico Italiano 9*, 1973, p. 113.

103. M. Poreh, J. L. Zakin, A. Brosh, M. Warshavsky. Drag Reduction in Hydraulic Transport of Solids. *Proc. of the ASCE, J. of Hydraulics Div. 95*, HY4, 1970, p. 903.

104. U. S. Bureau of Mines. Materials Handling Research: Hydraulic Transportation of Coarse Solids, by R. S. Fowkes, G. A. Wancheck. Report of Investigations 7283, 1969.

105. H. Kato, S. Goto, S. Yokoya. The Toms Effect of a Dilute Polymer Solution and its Application. *Bulletin JSME 15*, 1972, p. 492.

106. A. N. Shabrin. Investigation of Hydraulic Losses in Water Flows with Polymer Additives. *Fluid Mechanics — Soviet Research 2*, No. 1, 1973, p. 69.

107. R.J.E. Kerekes, W.J.M. Douglas. Viscosity Properties of Suspensions at the Limiting Conditions for Turbulent Drag Reduction. *Canadian J. Chem. Engr. 50*, 1972, p. 228.

108. R. J. Pirih, W. M. Swanson. Drag Reduction and Turbulence Modification in Rigid Particle Suspensions. *Canadian J. Chem. Engr. 50*, 1972, p. 221.

109. G. G. Duffy, K. Moller, A. L. Titchener. The Determination of Pipe Friction Loss. *Appita 26*, 1972, p. 191.

110. M. Moan, C. Wolff. On the Intrinsic Viscosity and the Non-Newtonian Behavior of Dilute Solutions of Carboxymethylcelluloses in Pure Water. *European Polymer Journal 9*, 1973, p. 1085.

111. W. D. McComb. The Turbulent Dynamics of an Elastic Fibre Suspension: A Mechanism for Drag Reduction. *Nature — Physical Science 241*, 1973, p. 117.

112. Western Co. Turbulent Heat Transfer to Viscoelastic Fluids, by G. T. Pruitt, et al. Report Cont. NAS7-369, 1966.

113. C. S. Wells. Turbulent Heat Transfer in Drag Reducing Fluids. *AIChE Journal 14*, 1968, p. 406.

114. M. Poreh, U. Paz. Turbulent Heat Transfer to Dilute Polymer Solutions. *Int. J. Heat and Mass Transfer 11*, 1968, p. 805.

115. M. K. Gupta. Turbulent Heat Transfer Characteristics of Viscoelastic Fluids. MME Thesis, University of Delaware, 1966.

116. M. K. Gupta, A. B. Metzner, J. P. Hartnett. Turbulent Heat-Transfer Characteristics of Viscoelastic Fluids. *Int. J. Heat and Mass Transfer 10*, 1967, p. 1211.

117. D. A. White. The Prediction of Heat and Mass Transfer Coefficients for Turbulent Pipe Flow of Dilute Polymer Solutions. *Chemical Engineering Science 24*, 1969, p.911.

118. General Electric Research and Development Center. Experimental Study of Heat Transfer in Viscoelastic Fluids, by J. C. Corman. Report 68-C-206, 1968.

119. G. Marrucci, G. Astarita. Turbulent Heat Transfer in Viscoelastic Liquids. *I&EC-Fundamentals 6*, 1967, p. 470.

120. K. A. Smith, G. H. Keuroghlian, P. S. Virk, E. W. Merrill. Heat Transfer to Drag-Reducing Polymer Solutions. *AIChE Journal 15*, 1969, p. 294.

121. A.White. Heat Transfer Characteristics of Dilute Polymer Solutions in Fully Rough Pipe Flow. *Nature 227*, 1970, p. 486.

122. R. L. Meek, A. D. Baer. The Periodic Viscous Sublayer Model and Heat Transfer to Drag Reducing Solutions. *AIChE Journal 16*, 1970, p. 1100.

123. H. Rubin. Scaling of Heat Transfer to Dilute Polymeric Solutions. *J. Hydronautics 5*, 1971, p. 148.

124. G. A. Hughmark. Heat and Mass Transfer for Turbulent Pipe Flow. *AIChE Journal 17*, 1971, p. 902.

125. Ye. M. Khabakhpasheva, B. V. Perepelitsa. Turbulent Heat Transfer in Weak Polymeric Solutions. *Heat Transfer – Soviet Research 5*, 1973, p. 117.

126. I. P. Chashin, N. T. Shalavin, Yu. N. Sukhushin. A Study of the Effect of Polymeric Additives on the Hydrodynamics and Heat Transfer of Turbulent Flow. *Heat Transfer – Soviet Research 5*, 1973, p. 38.

127. J. Vleggaar, M. Tels. Heat Transfer in a Heterogeneous Drag Reduction System. *Int. J. Heat and Mass Transfer 16*, 1973, p. 1629.

128. P. M. Debrule. Friction and Heat Transfer Coefficients in Smooth and Rough Pipes with Dilute Polymer Solutions. PhD Thesis, California Institute of Technology, 1972.

129. St. Anthony Falls Hydraulic Laboratory. The Influence of Drag Reducing Polymer on Radiated Noise from Rough Surfaces, by J. M. Killen. Project Report No.123, 1972.

130. J. F. Brady. An Experimental Study of the Vibration, Noise, and Drag of a Cylinder Rotating in Water and Certain Polymer Solutions. PhD Thesis, University of Rhode Island, 1973.

131. S. J. Barker. Radiated Noise from Turbulent Boundary Layers in Dilute Polymer Solutions. *Physics of Fluids 16*, 1973, p. 1387.

132. A. T. Ellis, J. W. Hoyt. Some Effects of Macromolecules on Cavitation Inception. *Cavitation Forum, ASME, New York, 1968*, p. 1.

133. A. T. Ellis, J. G. Waugh, R. Y. Ting. Cavitation Suppression and Stress Effects in High-Speed Flows of Water with Dilute Macromolecular Additives. *J. Basic Engineering, Trans. ASME, 92, D,* 1970, p. 459.

134. H. Lindgren, C.-A. Johnssen. Cavitation Inception on Head Forms – ITTC Comparative Experiments. *Appendix V of Report of Cavitation Committee, Proc. 11th International Towing Tank Conference, Tokyo, 1966, p. 219.*

135. J. W. Hoyt. Effects of High-Polymer Solutions on a Cavitating Body. *Proc. 11th International Towing Tank Conference, Tokyo, 1966, p. 233.*

136. C. Brennen. Some Cavitation Experiments with Dilute Polymer Solutions. *J. Fluid Mechanics 44,* 1970, p. 51.

137. J. W. Hoyt. Effect of Polymer Additives on Jet Cavitation. *Trans. 16th American Towing Tank Conference, Sao Paulo, 1971, Vol 1,* p. 7.0.

138. ──────────. Jet Cavitation in Polymer Solution. *Cavitation and Polyphase Flow Forum, ASME, New York, 1973,* p. 44.

139. Advanced Technology Center, Inc. Effect of High-Molecular Weight Polymer Additives on the Characteristics of Cavitation, by R. R. Walters. Report No. B-94300/2TR-32, 1972.

140. J. R. White. Propeller Cavitation in Solutions of Polyethylene Oxide. M. S. Thesis, Naval Postgraduate School, Monterey, 1971.

141. J. H. J. van der Meulen. Cavitation Suppression by Polymer Injection. *Cavitation and Polyphase Flow Forum, ASME, New York, 1973, p. 48.*

142. T. T. Huang. Comments on "Cavitation Inception: The Influence of Roughness, Turbulence, and Polymer Additives". *Trans. 16th American Towing Tank Conference, Sao Paulo, 1971,* Vol. 1, p. 6.10.

143. J. L. Lumley. Centerline-Bernoulli Equation for Quasisteady Dilute Polymer Flow. *Physics of Fluids 15,* 1972, p. 217.

144. M. Goldin, J. Yerushalmi, R. Pfeffer, R. Shinnar. Breakup of a Laminar Capillary Jet of a Viscoelastic Fluid. *J. Fluid Mechanics 38*, 1969, p. 689.

145. M. Gordon, J. Yerushalmi, R. Shinnar. Instability of Jets of Non-Newtonian Fluids. *Trans. Soc. Rheology 17*, 1973, p. 303.

146. F. W. Kroesser, S. Middleman. Viscoelastic Jet Stability. *AIChE Journal 15*, 1969, p. 383.

147. A. Sagiv, H. Rubin, R. Takserman-Krozer. On the Breakup of Cylindrical Liquid Jets. *Israel J. of Technology 11*, 1973, p. 349.

148 T. Hasegawa, Y. Tomita, Y. Mochimaru. A Study on Anomalous Turbulent Flows of Non-Newtonian Fluids – 2nd Report, Transitional Region from Laminar to Turbulent Flow. *Bulletin JSME 15*, 1972, p. 1093.

149. D. N. Jackley. Drag-Reducing Fluids in a Free Turbulent Jet. *International Shipbuilding Progress 14*, 1967, p. 158.

150. D. A. White. Velocity Measurements in Axisymmetric Jets of Dilute Polymer Solutions. *J. Fluid Mechanics 28*, 1967, p. 195.

151. R. A. Pownall, K. M. Kiser. Rate of Spread of Jets of Non-Newtonian Fluids. *I&EC Fundamentals 9*, 1970, p. 293.

152. G. E. Gadd. Turbulence Damping and Drag Reduction Produced by Certain Additives in Water. *Nature 206*, 1965, p. 463.

153. —————. Reduction of Turbulent Friction in Liquids by Dissolved Additives. *Nature 212*, 1966, p. 874.

154. Y. Goren, J. F. Norbury. Turbulent Flow of Dilute Aqueous Polymer Solutions. *Trans. J. Basic Engineering ASME, 89, D*, 1967, p. 814.

155. Hendon College of Technology. Turbulence and Drag Reduction with Polymer Additives, by A. White. Research Bulletin No. 4, 1967, p. 75.

156. J. Wu. Drag Reduction in External Flows of Additive Solutions. *Viscous Drag Reduction*, C. S. Wells, ed. Plenum Press, N. Y., 1969, p. 331.

157. S. J. Barker. Laser-Doppler Measurements on a Round Turbulent Jet in Dilute Polymer Solutions. *J. Fluid Mechanics 60*, 1973, p. 721.

158. S. A. Vlasov, V. N. Kalashnikov, B. F. Mul'chenko, B. S. Rinkevichyus, V. I. Smirnov. The Long-Range Nature of Turbulent Submerged Jets of Polymer Solutions. *Fluid Mechanics – Soviet Research 2*, No. 1, 1973, p. 108.

159. F. J. Lavoie. Water-Jet Machining. *Machine Design*, Feb. 22, 1973, p. 89.

160. A. M. Kudin, G. I. Barenblatt, V. N. Kalashnikov, S. A. Vlasov, V. S. Belokon'. Destruction of Metallic Obstacles by a Jet of Dilute Polymer Solution. *Nature – Physical Science 245*, 1973, p. 95.

161. S. A. Vlasov, V. N. Kalashnikov. Turbulent Diffusion of Heat in Jets of Dilute Polymer Solutions. *Nature 224*, 1969, p. 1195.

162. J. W. Hoyt, J. J. Taylor, C. D. Runge. The Structure of Jets of Water and Polymer Solution in Air. *J. Fluid Mechanics 63*, 1974, p. 635.

163. J. Wu. Lift Reduction in Additive Solutions. *J. Hydronautics 3*, 1969, p. 198.

164. T. Kowalski. Effect of Polymer Additives on Propeller Performance. *J. Hydronautics 5*, 1971, p. 11.

165. Mitteilungen der Versuchsanstalt für Wasserbau und Schiffbau, Berlin. Über die Verminderung des Reibungswertes von Grenzschichtströmungen viskoelastischer Flüssigkeiten – Teil II, by F.-P. Kilian. Heft 52, 1970.

166. F.-P. Kilian. Verminderung des Propellerwirkungsgrades durch Fadenmoleküle. *Umschau*, Heft 24, 1970, p. 786.

167. T. Sarpkaya. Lift and Drag Measurements on a Hydrofoil in Dilute Polyox Solutions. *Nature 241*, 1973, p. 114.

168. H. Kawada, T. Tagori. Some Experiments on Two-Dimensional Hydrofoils in Polymer Solutions. *Proc. Annual Meeting JSME, 1973*.

169. Oceanics, Inc. An Experimental Study of the Lift and Drag of a Hydrofoil with Polymer Ejection, A. F. Lehman, R. T. Suessmann. Report No. 72-94, 1972.

170. H. Canham, J. Catchpole, R. Long. Boundary Layer Additives to Reduce Ship Resistance. *The Naval Architect, J. of the Royal Institute of Naval Architects*, No. 2, July 1971, p. 187.

171. L. H. Henderson. Effect of Polyethylene-Oxide Solutions on the Performance of a Small Propeller. M. S. Thesis, Naval Postgraduate School, Monterey, 1971.

172. J. V. Sanders, L. H. Henderson, R. J. White. Effects of Polyethylene-Oxide Solutions on the Performance of a Small Propeller. *J. Hydronautics 7*, 1973, p. 124.
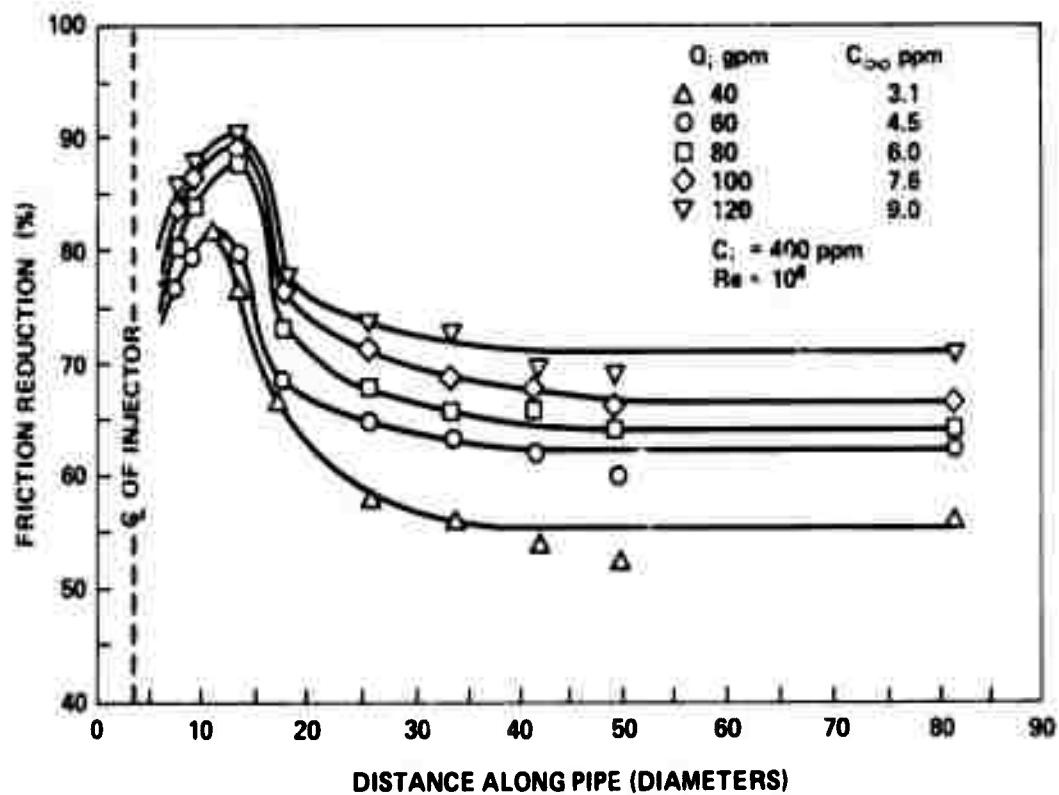
Figure 1. Friction reduction in a 12-inch pipe, obtained by injecting various flow rates, Q_i, of poly(ethylene oxide) at 400-ppm concentration (C_i), to give final concentrations in the entire pipe of C_∞.
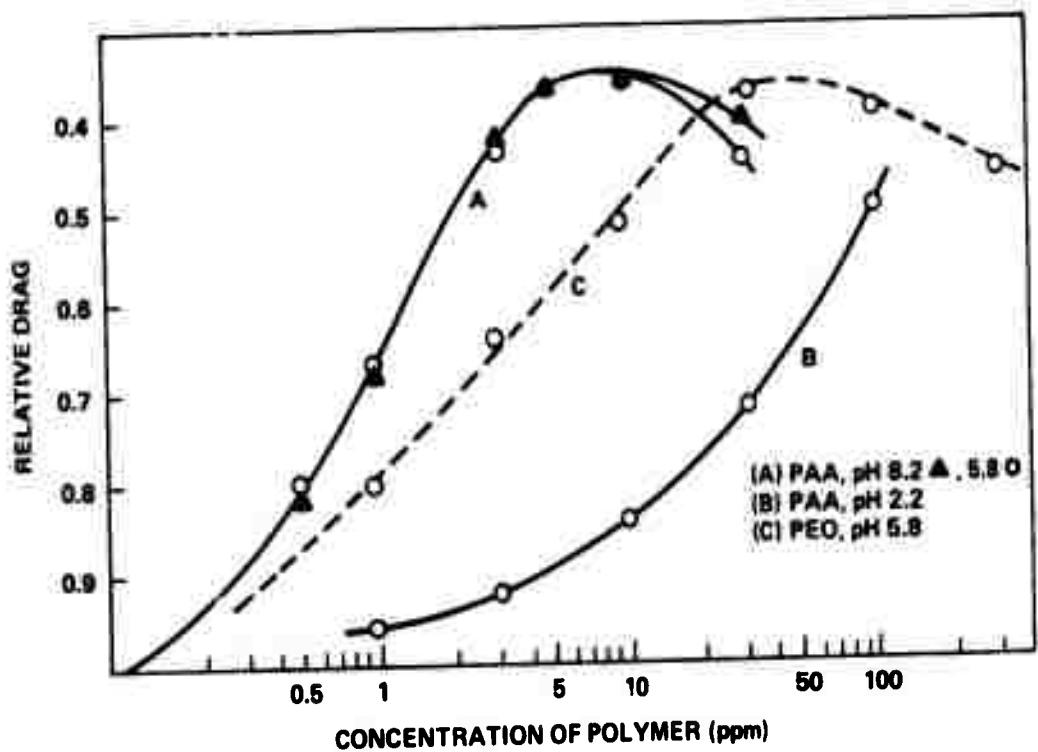
Figure 2. Effect of pH on polyacrylic acid (PAA), compared with poly(ethylene oxide) (PEO), in a 0.6-cm tube at a Reynolds number of 11,700.
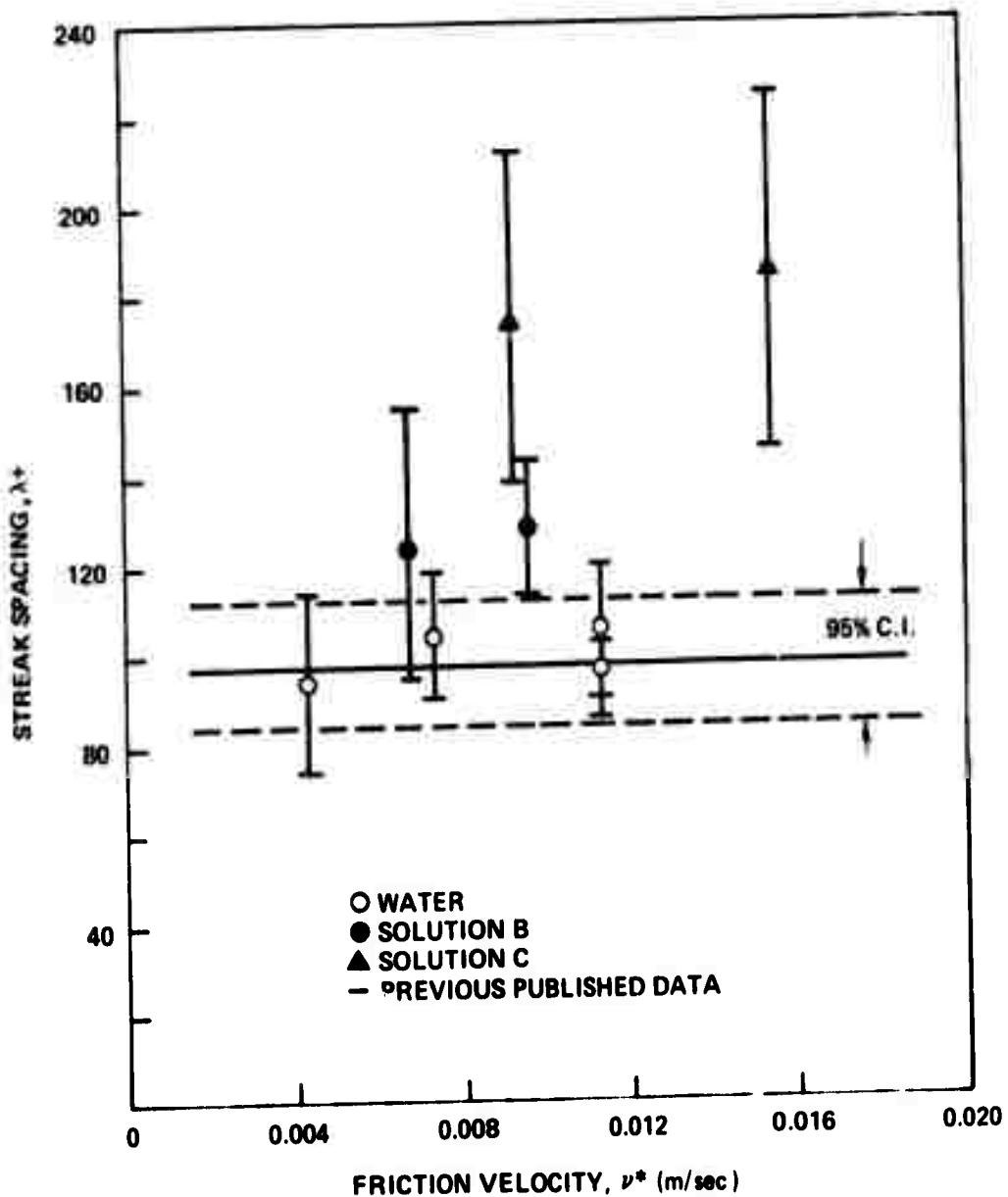
Figure 3. Non-dimensional streak spacing, λ^+, as a function of friction velocity, v^*, for water and two solutions of poly(ethylene oxide) in channel flow.

34
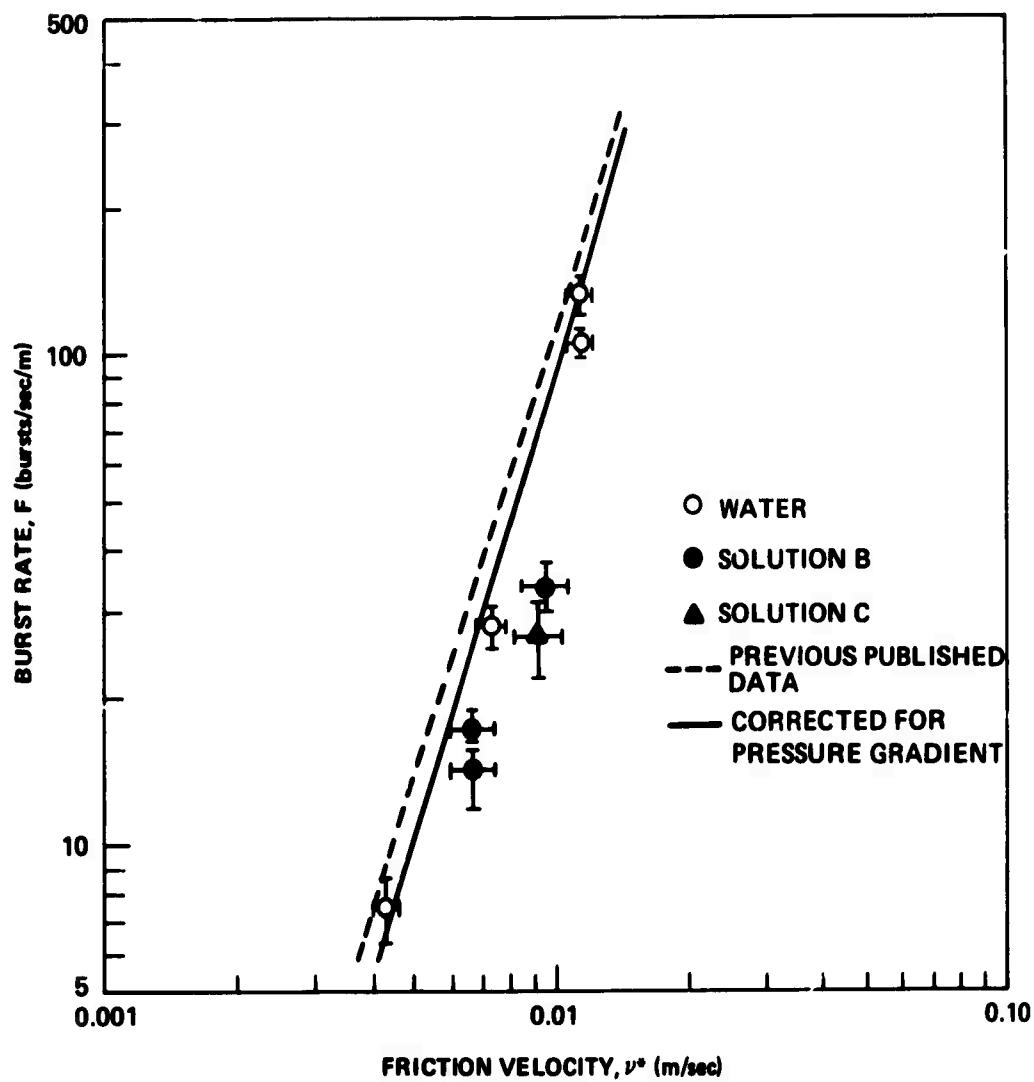
Figure 4. Average turbulent burst rate, F, as a function of friction velocity, ν^*, for water and two solutions of poly(ethylene oxide) in channel flow.
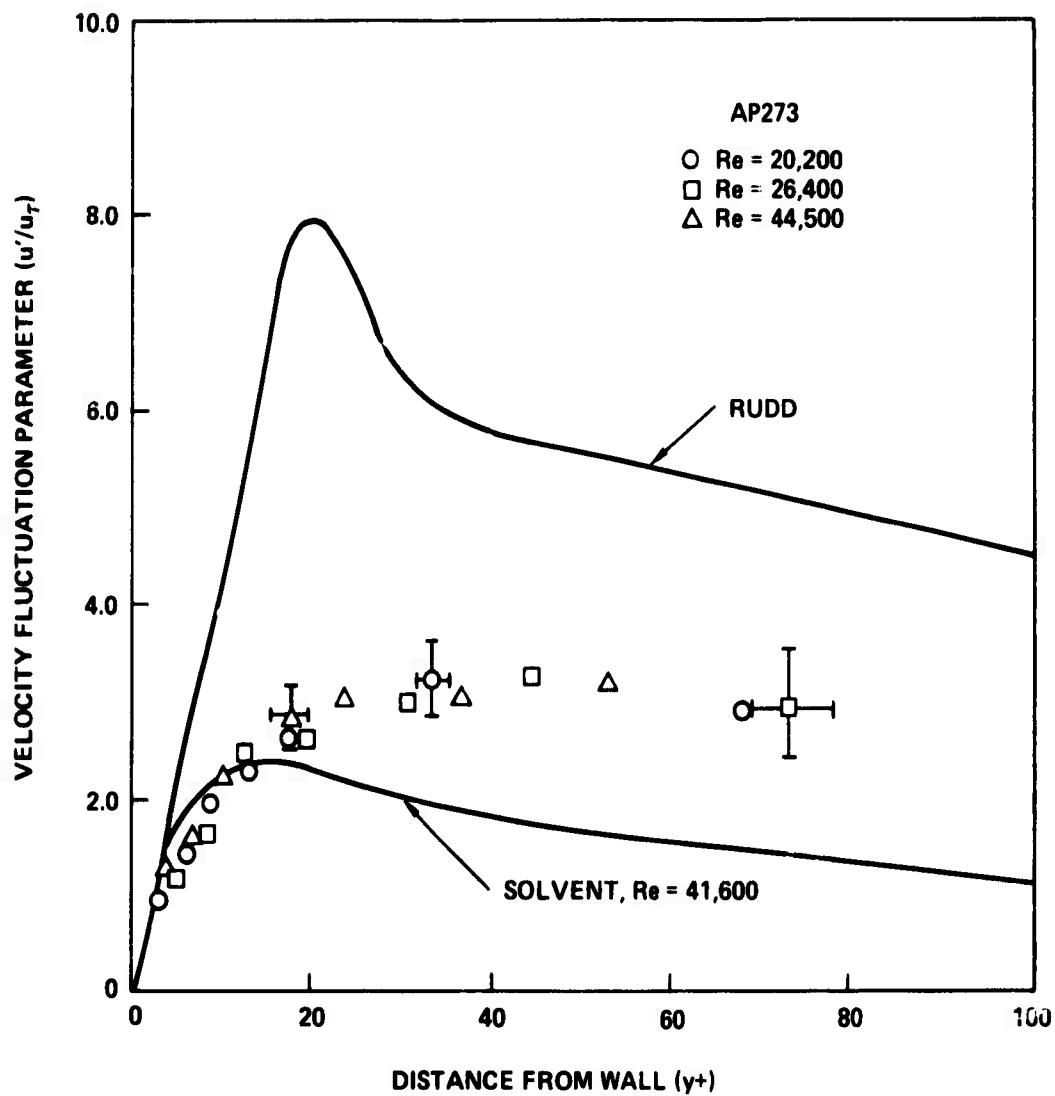
Figure 5. Turbulent intensities measured in a channel by Reischman [30] as a function of distance from wall for a solution of 100-ppm polyacrylamide, Separan AP 273.
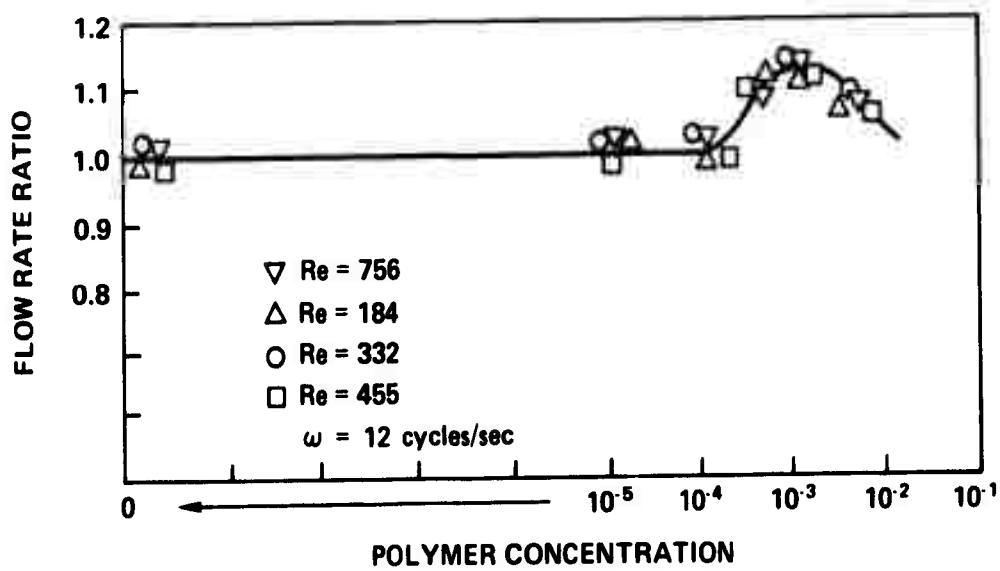
Figure 6. Increased flow rate in pulsed laminar flow of poly(ethylene oxide) in a 11.8-mm tube.
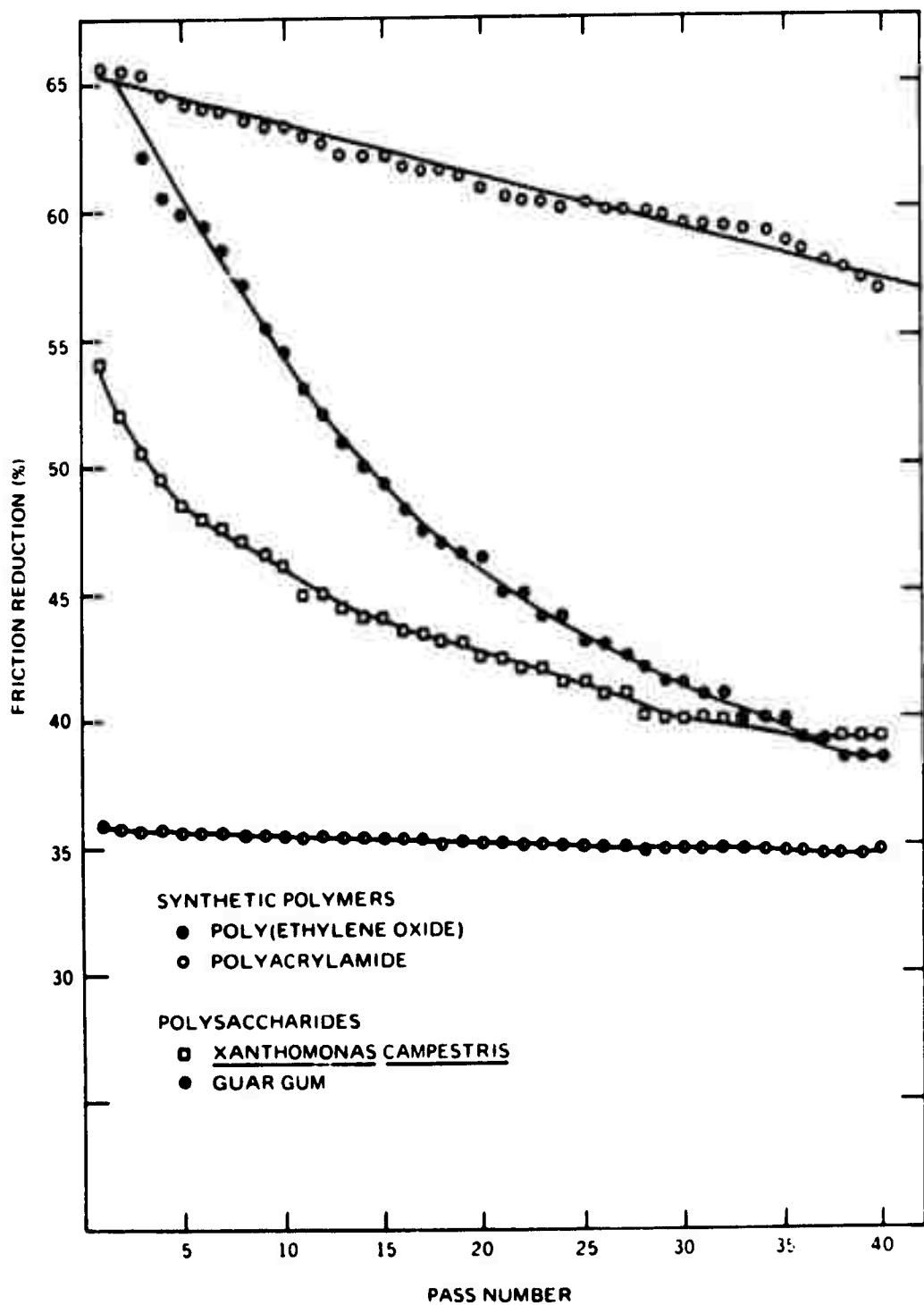
Figure 7. Effect of repeated passes through a small pipe-flow apparatus on the drag reduction of various polymers, all at 40-ppm concentration.
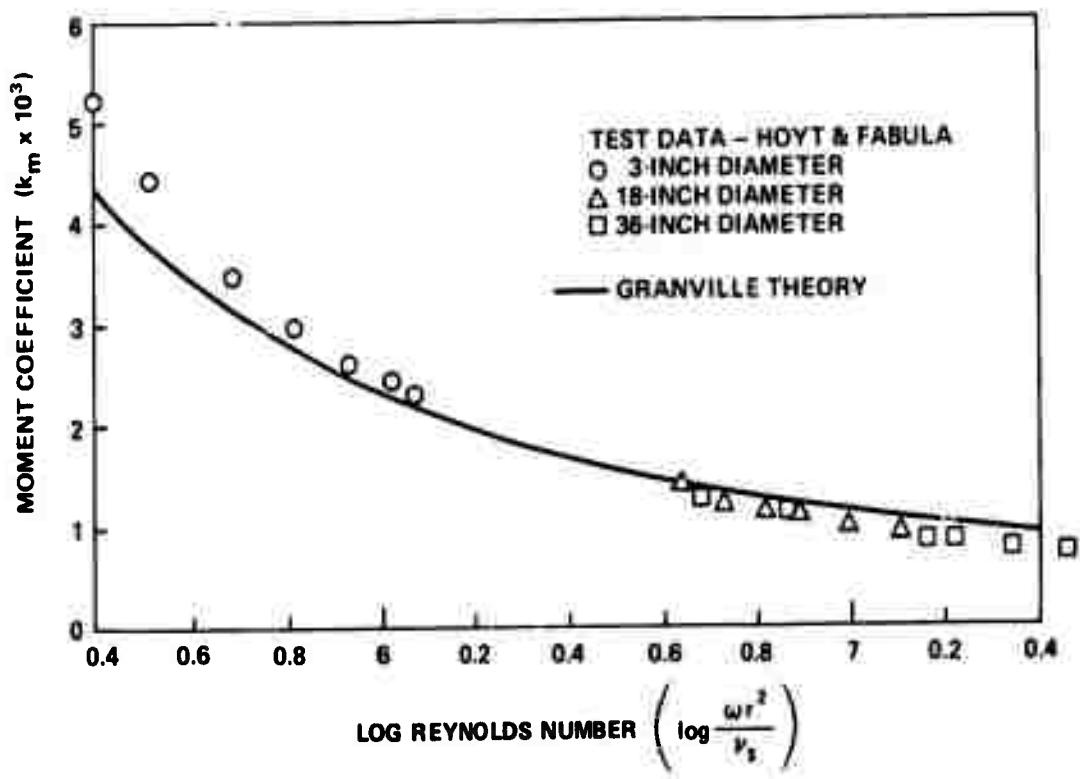
Figure 8. Granville's theoretical prediction of maximum drag reduction on rotating disks in polymer solutions, compared with test data.
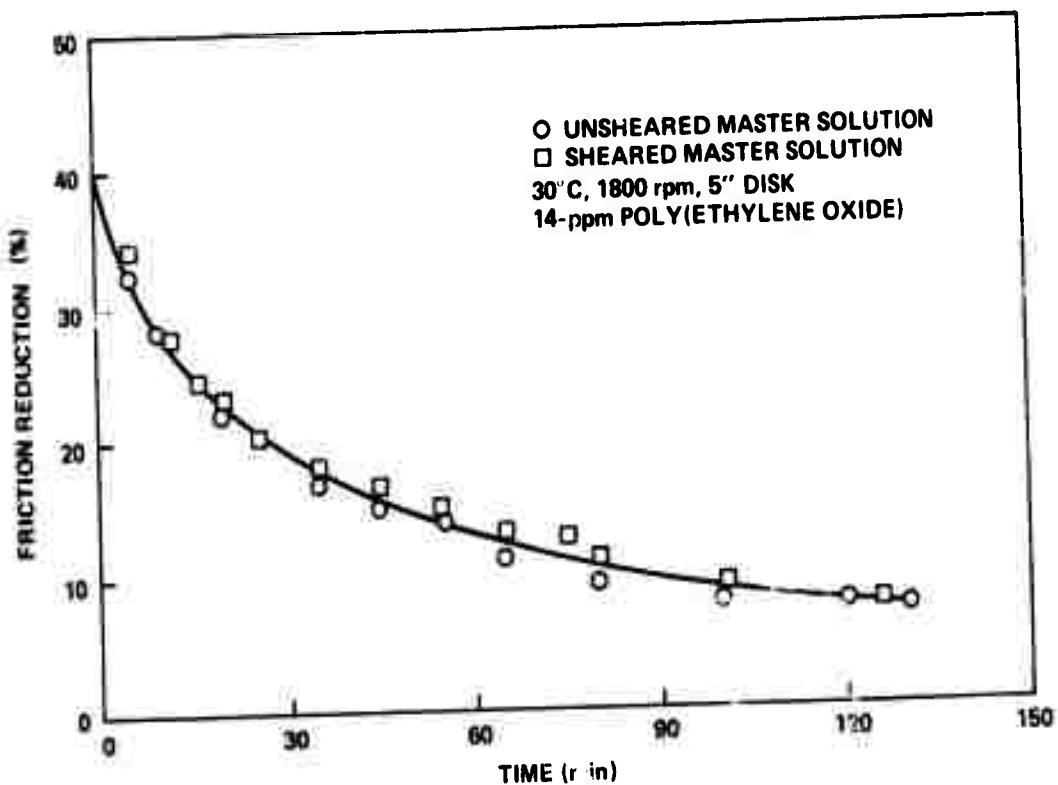
Figure 9. Effect of shearing a 1 % "master" solution of poly(ethylene oxide) on friction reduction degradation after dilution to 14 ppm. The sheared "master" solution had a viscosity reduction of 50 % compared to the unsheared "master" solution.
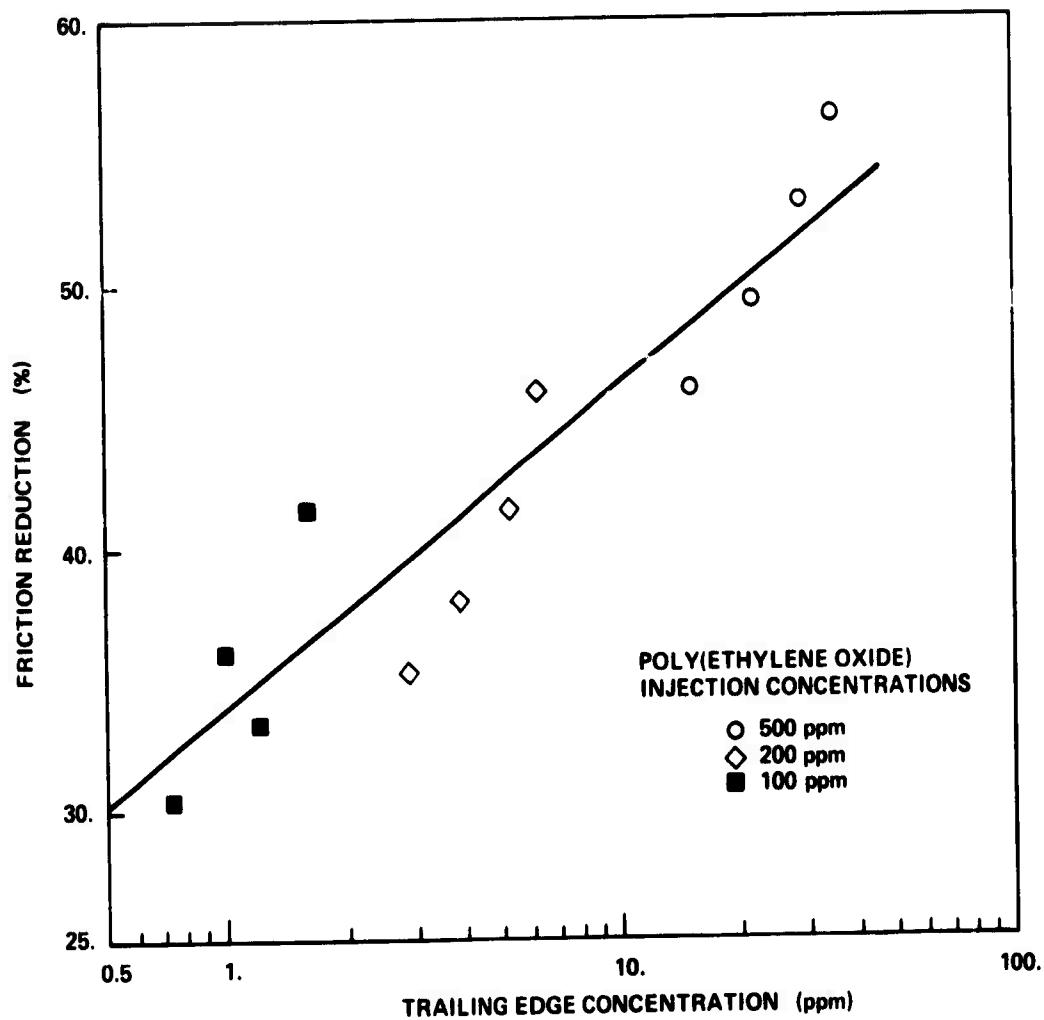
Figure 10. Drag reduction on a 10-ft-long flat plate as a function of trailing-edge polymer concentration.
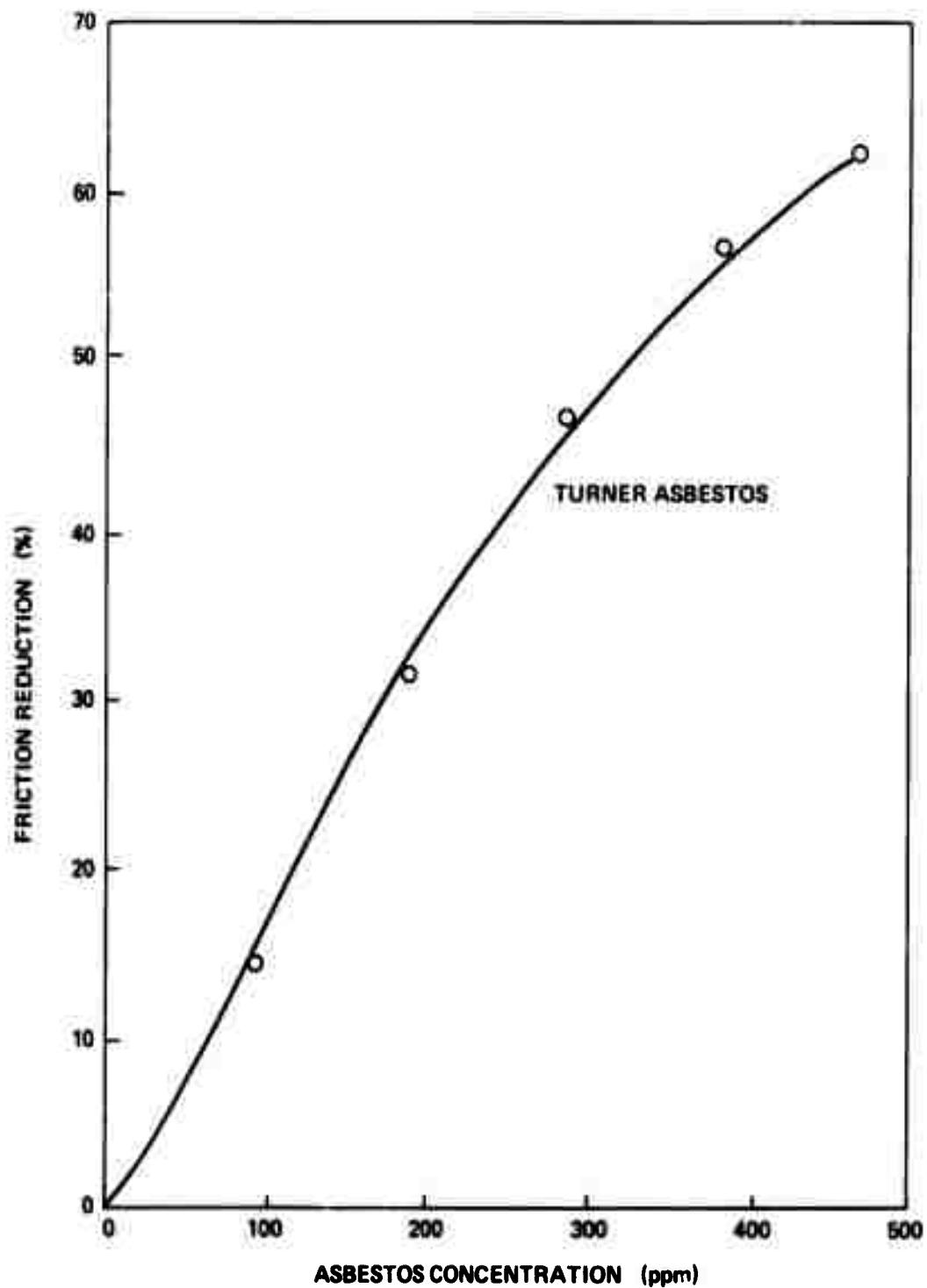
Figure 11. Drag reduction of asbestos fibers in turbulent-flow rheometer. The asbestos is suspended in an 0.8 % solution of Aerosol OT surfactant.

42
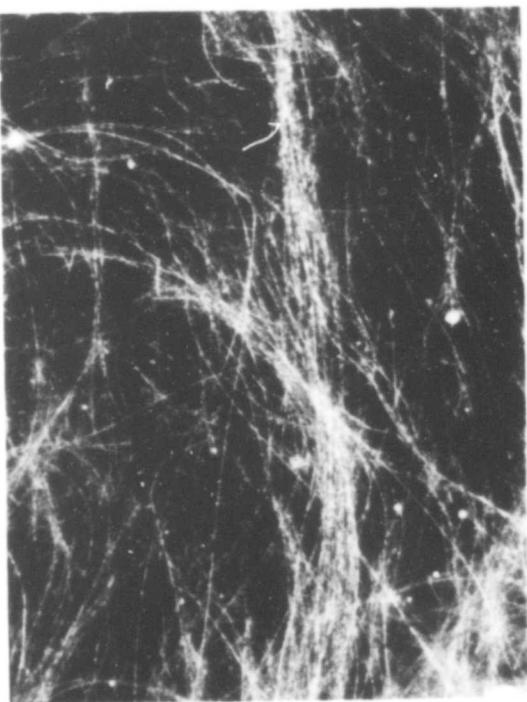
Figure 12. Photomicrograph at 304X of a very effective drag-reducing asbestos fiber (Johns-Manville 3T12).

HEAT TRANSFER COEFFICIENT

1. WATER } SMOOTH
2. 10 ppm } TUBE
3. 50 ppm }
4. WATER } MEDIUM
5. 10 ppm } TUBE
6. 50 ppm }
7. WATER } ROUGH
8. 10 ppm } TUBE
9. 50 ppm }

PR = 10.3

5

2

10^{-3}

5

2

10^{-4}

7

4

8

1

5

9

2

3

6

20   100   200

REYNOLDS NUMBER x 10^{-3}
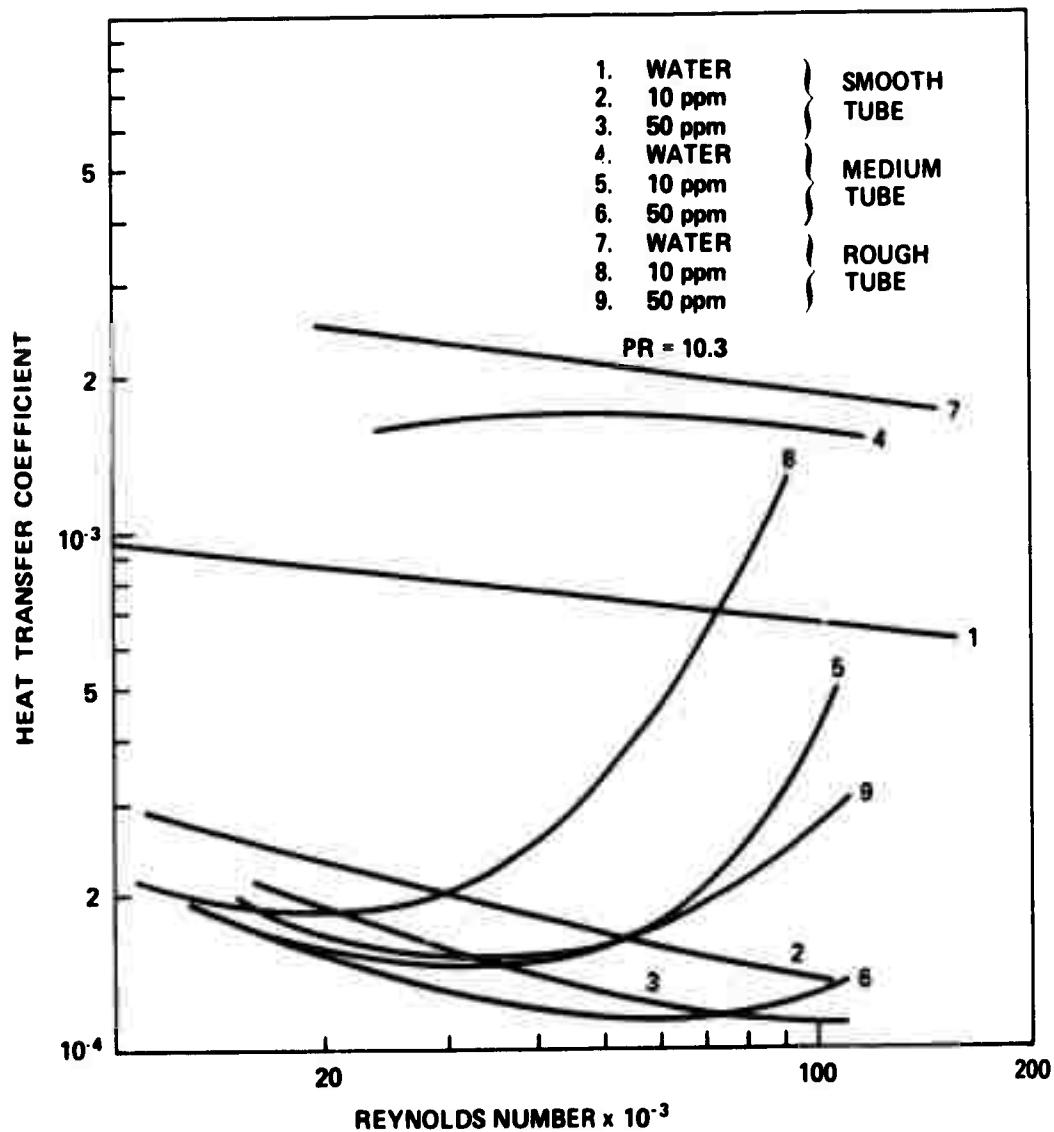
Figure 13. Effect of poly(ethylene oxide) on heat transfer coefficient at a Prandtl No. of 10.3.

44
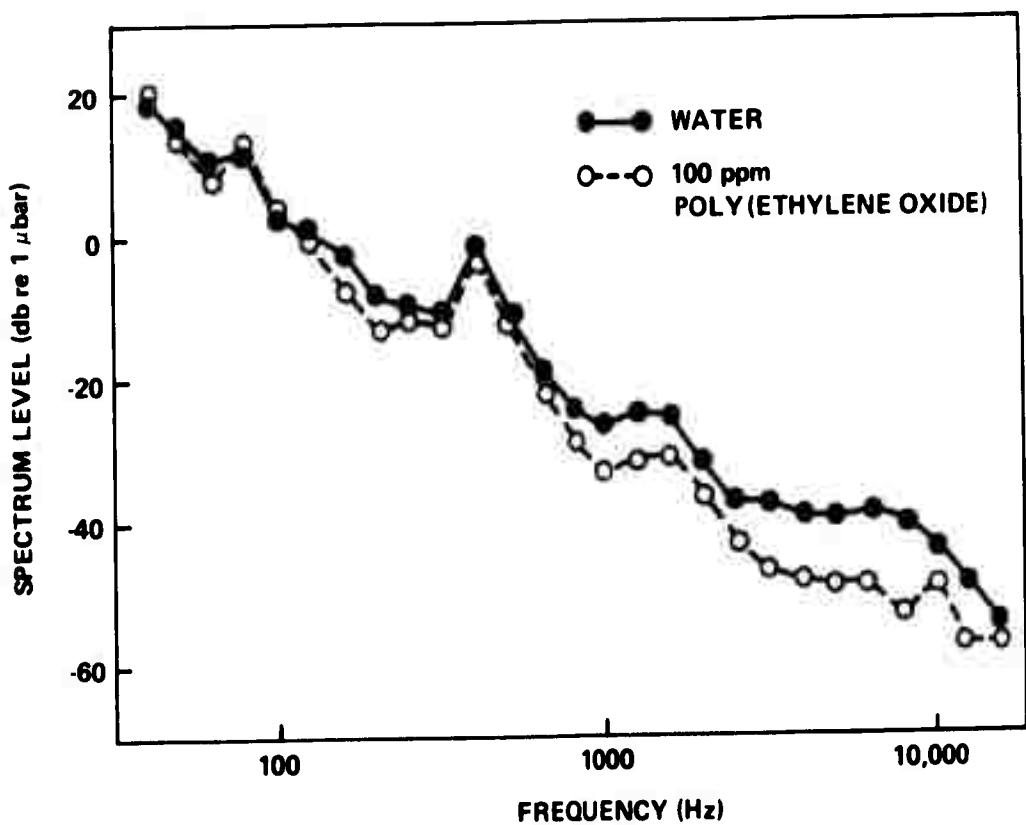
Figure 14. Effect of poly(ethylene oxide) on radiated flow noise from a simulated flat plate.
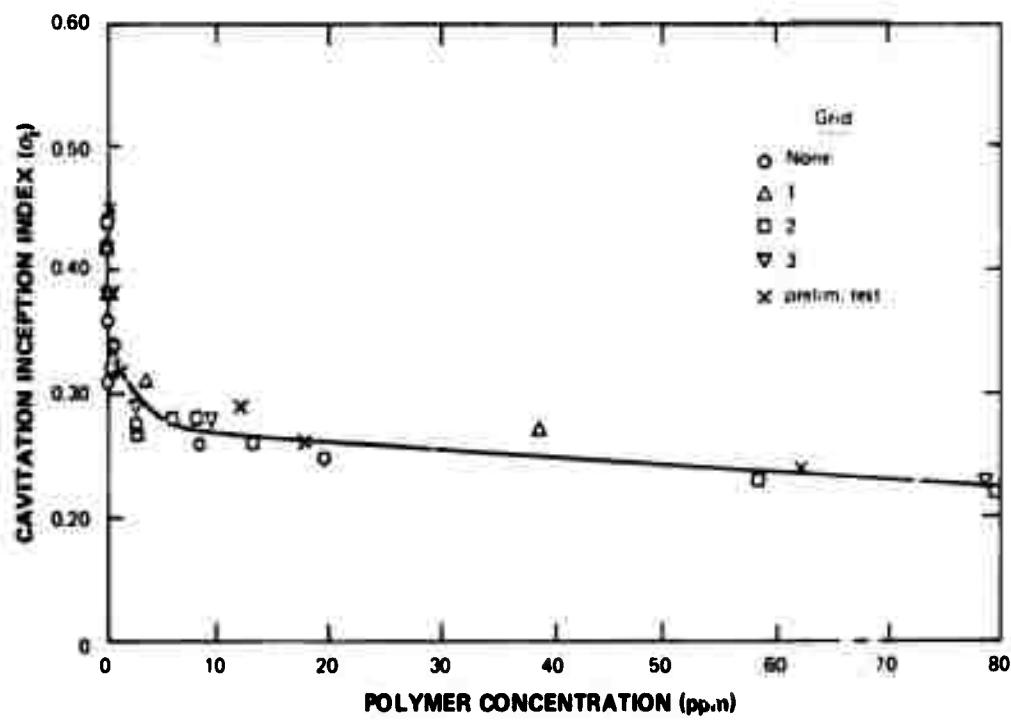
Figure 15. Effect of poly(ethylene oxide) on cavitation inception in a small jet; symbols refer to various values of upstream turbulence.
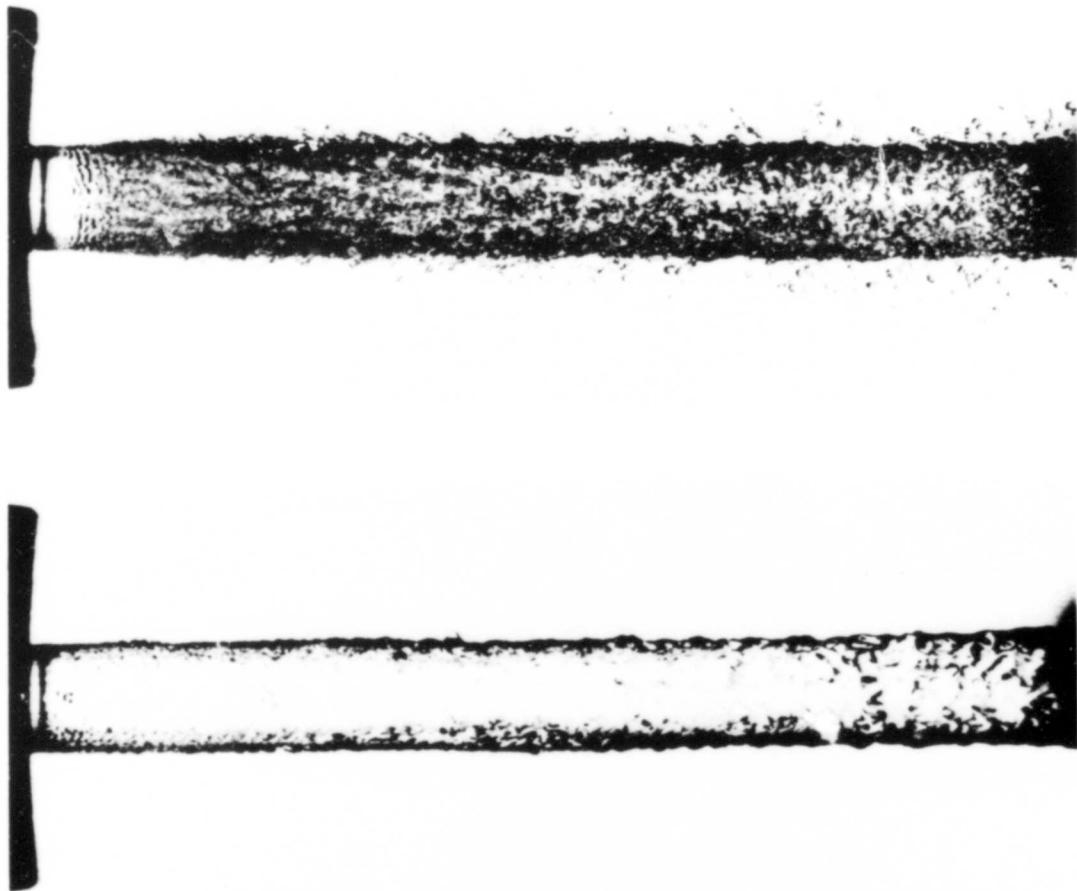
Figure 16. High-speed photograph of a jet of water (above) and 200-ppm poly(ethylene oxide) (below) emerging from a 1/4-in.-diameter nozzle with 50-psi nozzle base pressure. Flow is left to right.

47

Figure 17. Breakup of jets, 6 ft from nozzle exit. Water (above) and 200-ppm poly(ethylene oxide) (below) from a 1/4-in.-diameter nozzle with 50-psi nozzle base pressure. Flow is left to right.
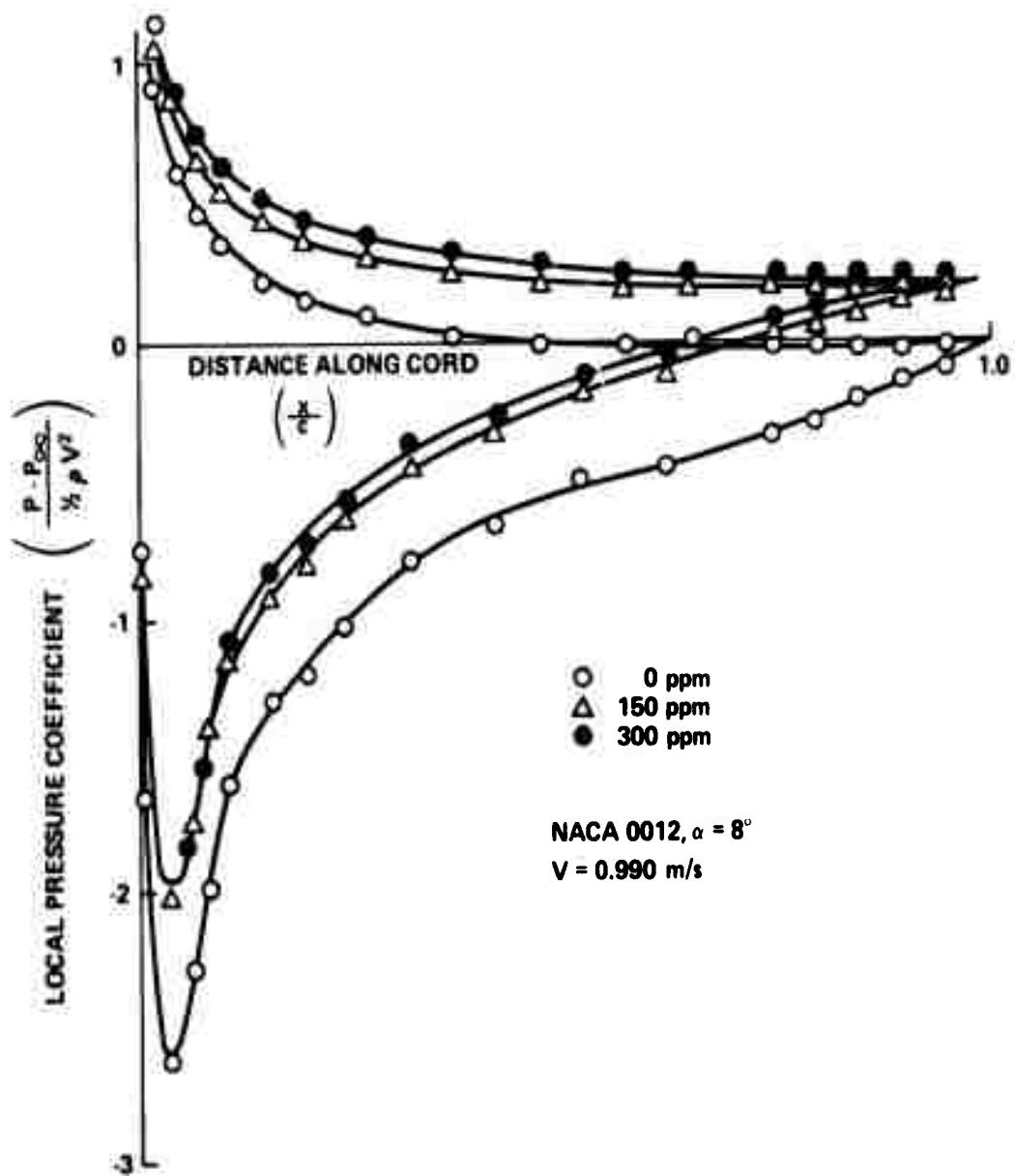
Figure 18. Pressure distribution on a NACA 0012 airfoil at an angle of attack of 8° for various concentrations of polyacrylamide, Separan AP-30.

0 ppm
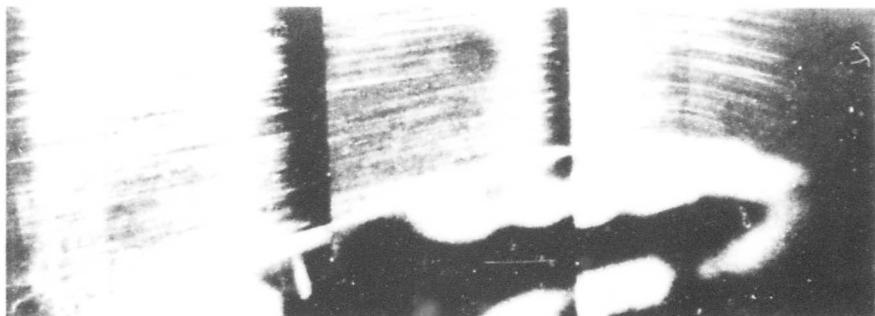
150 ppm
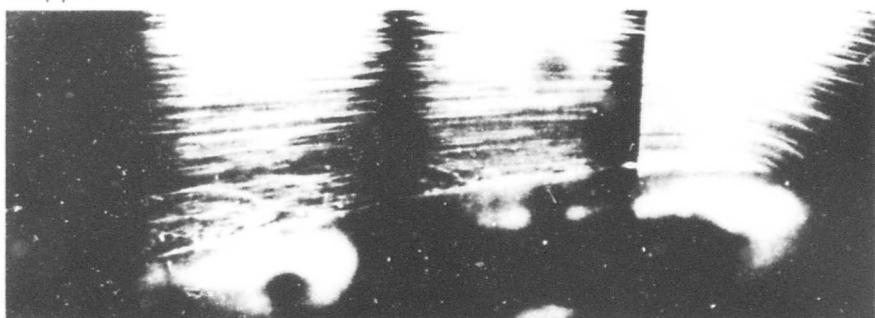
300 ppm

$\alpha = 14°$

Figure 19. Bubble-streak photographs of flow around NACA 0012 airfoil at angle of attack of 14°. Flow speed 1.0 m/sec, with various concentrations of polyacrylamide, Separan AP-30.

50
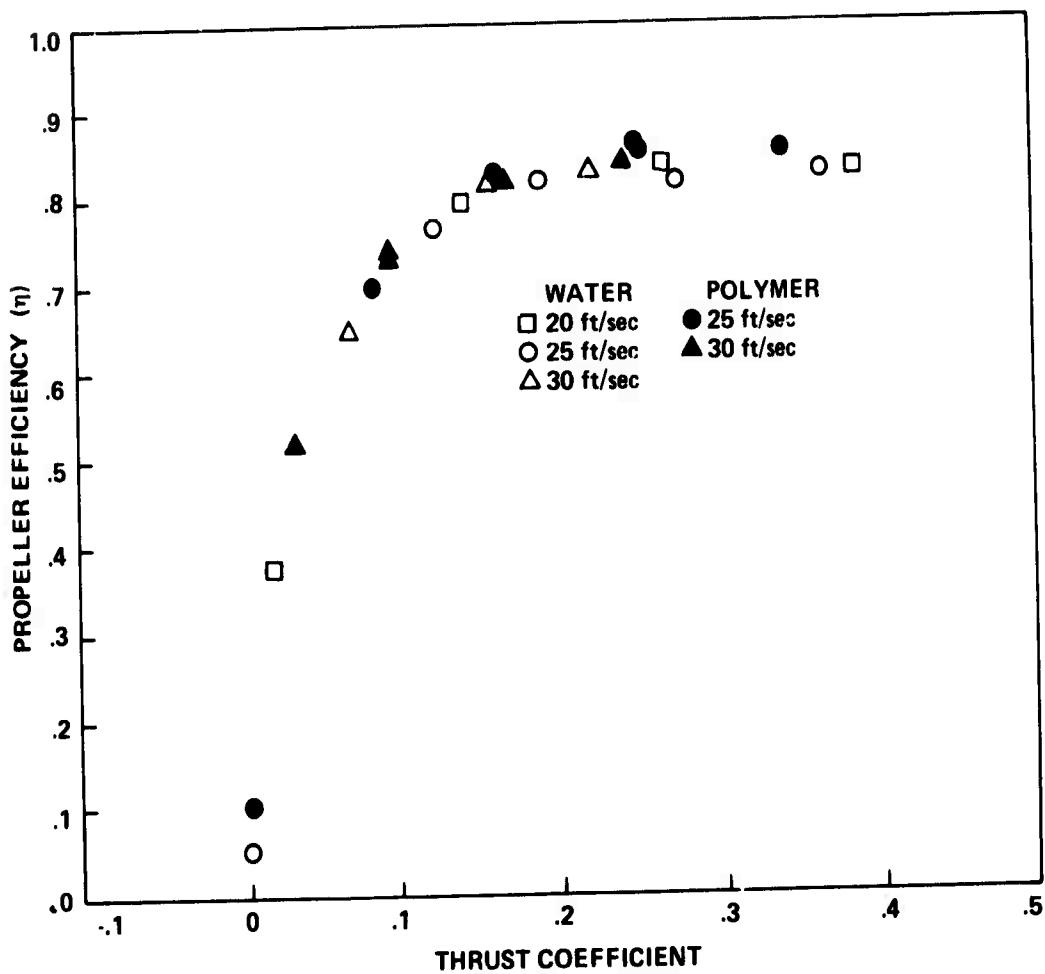
Figure 20. Effect of poly(ethylene oxide) on efficiency of open-water propeller. Polymer concentration approximately 4-8 parts per million.